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THESIS

COMPARISON OF THE PERFORMANCE AND CAPABILITIES OF FEMTOCELL VERSUS WI-FI NETWORKS

by

James K. Bare

September 2012

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13. ABSTRACT (maximum 200 words)

Femtocells are low power base stations that communicate through a licensed spectrum with the intent to improve coverage and performance of voice and broadband services. The Femtocell works through a cellular network provider to enhance cellular portable/mobile devices especially in locations where coverage by cellular systems using large cells is weak and intermittent.

The use of smartphones, tablets, and other wireless devices is becoming increasingly prevalent and is driving the need for innovations in wireless data technologies to provide more capacity, higher speed connections, and higher quality of service. Femtocells can provide a useful way for mobile operators to offer a better user experience and deliver broadband services indoors consistently and reliably for a comparable context of application, distances, and obstacles.

In this thesis we will conduct a quantitative and qualitative analysis of Femtocell performance in comparison to that of Wi-Fi. Using COTS Femtocell and Wi-Fi technology an analysis will be conducted to establish which of the two is the better means of bringing internet connectivity to forward deployed forces. The potential benefits of this research are a better understanding of the advantages and disadvantages of Femtocell and Wi-Fi networks in simulated garrison and deployed environments.

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COMPARISON OF THE PERFORMANCE AND CAPABILITIES OF FEMTOCELL VERSUS WI-FI NETWORKS

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LIST OF ACRONYMS AND ABBREVIATIONS

2G	Second Generation Wireless Telephone Technology
3G	Third Generation Wireless Telephone Technology
3GPP	Third Generation Partnership Project
4G	Fourth Generation Wireless Telephone Technology
ACS	Auto Configuration Services
AP	Access Point
BS	Base Station
BSS	Basic Service Set
BSSID	Basic Service Set Identification
CDMA	Code Division Multiple Access
COTS	Commercial Off The Shelf
CPE	Customer Premise Equipment
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DPDCH	Dedicated Physical Data Channel
DIFFSERV	Differentiated Services
DS	Distribution System
DSL	Digital Subscriber Loop
EAP	Extensible Authentication Protocol
EVDO	Evolution Data Optimized
FAP	Femtocell Access Point
GPS	Global Positioning System
GSM	Global System for Mobile
HARQ	Hybrid Automatic Repeat Request
HNB	Home Node B
HSDA	High Speed Down-Link Access
HSUPA	High Speed Up-Link Packet Access
HTTP	Hyper Text Transfer Protocol
IBSS	Integrated Basic Service Set

IEEE	Institute of Electrical and Electronics Engineers
IKEV2	Internet Key Exchange Version 2
INTSERV	Integrated Services
IP	Internet Protocol
IPSEC	Internet Protocol Security
ISM	Industrial Scientific and Medical
LAN	Local Area Network
LL	Link Layer
LTE	Long Term Evolution
MAC	Media Access Control Layer
MOS	Mean Opinion Score
OFDMA	Orthangonal Frequency Division Multiple Access
PHY	Physical Layer
PING	Packet Internet Groper
PSTN	Public Switched Telephone Network
QOS	Quality of Service
RSS	Received Signal Strength
RSVP	Resource Reservation Protocol
RTCP	Real-time Transfer Control Protocol
RTP	Real-time Transfer Protocol
SNR	Signal-to-Noise Ratio
TCP	Transmission Control Protocol
TR	Technical Report
UAM	Universal Access Method
UDP	User Datagram Protocol
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telecommunications System
UNC	UMA Network Controller
URL	Uniform Resource Locator
VOIP	Voice Over Internet Protocol

WEP	Wired Equivelant Protocol
WI-FI	Wired Fidelity
WLAN	Wireless Local Area Network

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To Marcy, my beautiful and loving wife, I would not be where I am today if it were not for your dedication and devotion. Thank you for everything, and especially for always being there for me and believing in me. To our awesome children, Marty, Elijah, Zachary, Nicholas, Gabriel, and Caleb, your support and understanding not only during this demanding endeavor but throughout my entire career has empowered me more than you will ever know. Thank you for being an amazing family.

To my advisors, John Gibson and Dr. Douglas MacKinnon, your support and mentorship throughout this process was instrumental in my success here at NPS. I consider myself fortunate to have worked with you and to have been guided along by you. Thank you both sincerely.

I. INTRODUCTION

A. BACKGROUND

Femtocells are known by most as a type of home cellular base-station. Commercially, it has names like Network Extender (Verizon), Microcells (AT&T), and Airave (Sprint), among others, worldwide. It is a low-power base station that communicates through a licensed spectrum with the intent to improve indoor coverage and performance of voice and broadband services. The femtocell, working through a cellular network provider, enhances connectivity for cellular phones, smartphones, and other portable/mobile devices, especially in locations where coverage by cellular systems using large cells is weak and intermittent (i.e., indoors or remote areas). Ultimately, the user's mobile devices are connected via the femtocell to a backbone network supplied by an Internet service provider.

Although the femtocell architecture may seem different to the casual user, it is actually the same connection that a normal mobile device uses to access Internet connectivity. The difference is that a standard device connects through outdoor high power base stations and the femtocell is its own access point base station. This smaller localized base station provides very stable and efficient Internet connections.

Femtocell network technology may seem like a new technology but early femtocell research was introduced in the late 1990s and has grown dramatically in the last decade. Both the general public and commercial mobile operators have shown increased interest in ways to improve upon and expand this technology through 3G and LTE/4G.

Questions often asked are, "Why do we need femtocells when there is Wi-Fi technology," and "Which one is better for the potential mobile device user?" The purpose of this thesis is to analyze femtocell and Wi-Fi network capabilities and performance to determine which is the better platform for military use in a potential tactical network.

B. PURPOSE

The purpose of this thesis is to conduct an analysis of femtocell performance in comparison to that of Wi-Fi from the user's point of view. Using commercial-off-the-shelf (COTS) femtocell and Wi-Fi technology, an analysis will be conducted to establish which of the two is the better means of bringing Internet connectivity to forward deployed military members. In order to accomplish this we will perform performance tests in the areas of Internet connectivity, uploading and downloading speeds, and Voice over IP (VoIP) in both ideal conditions and in realistic (less than ideal) conditions. The potential benefits of this research to the defense establishment are a better understanding of the advantages and disadvantages of femtocell and Wi-Fi networks in simulated garrison and deployed environments.

C. SCOPE

Our objective for this research is a better understanding and analysis of femtocell network performance, especially as compared to those of Wi-Fi. Our analysis will be based on several performance tests between a femtocell and a Wi-Fi in the areas of accessing the Internet, streaming data, and voice over IP (VoIP).

In order to perform these tests we utilize a COTS Wi-Fi router and femtocell. The first series of tests will be baseline performance tests that will establish the basic performances in ideal conditions. We will then perform the same series of tests in a realistic environment (non-ideal situations).

As mentioned earlier, the targeted areas of testing are accessing the Internet, streaming data, and VoIP. These areas were chosen because they are the most used methods of utilizing networks. Each of these areas can also be used by members of the military in both garrison and deployed environments.

The first area is accessing the Internet through Hyper Text Transfer Protocol (HTTP). HTTP is the underlying protocol that is used by the World Wide Web. It defines the way in which messages are formatted and transmitted, as well as, what actions need to be taken. HTTP is used in every action of the process of accessing the web.

Real-time Transport Protocol (RTP) is the underlying protocol in our next area of evaluation: streaming data. RTP basically standardizes packet formats for delivering audio and video over IP networks. RPT is used for streaming media, teleconferencing, and real time data.

The final area of testing is VoIP. VoIP is the process of transmitting voice traffic over IP-based networks. VoIP essentially compresses data packets during transmission which allows more data to be handled over the carrier. As a result VoIP can not only handle multiple callers at once, but it can also (through software applications) transmit video and data.

As stated, the testing will be conducted in both ideal and non-ideal environments. Our definition of an ideal situation is one where we are located in the same room as the Wi-Fi router and Femtocell access point. The non-ideal environments consist of moving further away from the router and Femtocell, and include obstacles such as walls and floors. The number of users on the network is also included in our non-ideal environments.

D. LITERATURE REVIEW

Femtocells first came to light in 1996 through Silventoinen et al.'s, "Analysis of a new channel access method for home base-stations." It described the potential of extending the concept of a home base-station. He described a simple architecture of a cellular network that used a peculiar Total Frequency Hopping. This basic idea led to suggestions of a requirement to double frequency re-use in both indoor and outdoor environments, years earlier covered in Kinoshita et al.'s "Frequency common use between indoor and cellular radio research on frequency channel doubly reused cellular system" (1989). From 1996 to present there has been significant research on femtocells. Joseph Boccuzzi et al.'s "Femtocell Design and Applications" (2011) and Jie Zhang et al.'s "Femtocells Technologies and Deployment" (2010) are some of the most recent and extensively cover the subject of femtocells with an emphasis on the deployment and use of the equipment in a more commercial manner.

The 3rd Generation Partnership Project (3GPP), a partnership that produces technical specifications and reports pertinent to 3rd generation cellular systems, has issued numerous releases that prepare and support the continuous evolution of femtocells (3GPP releases 9 and 10, TS 25.467 and 25.306, TR 21.905). In 2007, the Femto Forum was created to promote wide-scale adoption of femtocells. This forum has played a role in ensuring that the standards were agreed upon and released to the public. Publications from this forum, “Interference Management in UTMS Femtocells” (2010) and “Regulatory Aspects of Femtocells” (2011), speak to the challenges of interference and regulatory issues with which the femtocell community is currently dealing. There are also technical literature and periodic reviews that deal heavily with LTE prospects and transmission issues (V. Chandrasekhar et al.’s “Femtocell Networks: a Survey” (2008), and D. Knisely et al.’s “Standardization of Femtocells in 3GPP” and “Standardization of Femtocells in 3GPP2” (both in 2009). In 2010, methods to improve joint macro level and femtocell level frequency assignments and alternate optimized frequency reuse schemes are addressed in Y. Haddad et al.’s “Femtocell SINR Performance Evaluation” (2010). Additional challenges and issues relating to combining and synchronizing signals from other base stations are studied in S. Kim et al.’s “Performance Analysis of LTE Enterprise Femtocell Using Cooperative Downlink Transmission Scheme” (2011). This study stresses the need to utilize the LTE FDM scheme to get overlapping resources, which lead to better SINR and reinforced signals.

Analyses of mixed Macro-cell and Femtocell cases are seen in B. Kaufman et al.’s “Femtocells in Cellular Radio Networks with Successive Interference Cancellation”(2011). These analyses look to introduce a Femtocell power control process that does not require coordination with macro-cells. The ultimate goal is defining an optimal Macro-cell-to-Femtocell hand-off. Other interference issues involved with Heterogeneous Networks (HeTNeT) are referenced in D. Lopez-Perez et al.’s “Enhanced Intercell Interference Coordination Challenges in Heterogeneous Networks” (2011). Lopez-Perez et al deals specifically with the control channel degradation problems and the application of different power control techniques in Femtocells.

Recently, numerous publications have been released dealing with the very important issues of resource assignments and optimization. A few examples of these are: G. de La Roche et al.'s "Selforganization for LTE enterprise femtocells" (2010), Y. Haddad et al.'s "Analysis of an Efficient Channel Assignment Scheme for Femtocell" (2011), F. Tariq et al.'s "Dynamic Fractional Frequency Reuse Based Hybrid Resource Management for Femtocell Networks" (2011), S. Das et al.'s " Issues in Femtocell Deployment in Broadband OFDMA Networks: 3GPP-LTE a case study" (2011), and X. Chu et al.'s "Resource Allocation in Hybrid Macro/Femto Networks" (2010).

D. de la Roche et al.'s "Selforganization for LTE enterprise femtocells" (2010) discusses methods and relating problems with the use of multiple LTE femtocells in different environments. De la Roche et al proposes that the best global throughput can be achieved by a specifically proposed self-organizing network technique. The need for Femtocell Access Points to share spectrum and several algorithms to share this spectrum across multiple Femtocell Access Points (FAPs) are explored in Y. Haddad et al.'s "Analysis of an Efficient Channel Assignment Scheme for Femtocell" (2011). Haddad et al states that a central database that holds information on all FAPs in most cases offers the better performance. Methods of using Hybrid Resource Management Algorithms (HRMA) for down-link OFDMA purposes in order to offer better performance with a larger number of nodes is discussed in F. Tariq et al.'s "Dynamic Fractional Frequency Reuse Based Hybrid Resource Management for Femtocell Networks" (2011). When referring to broadband, S. Das et al.'s "Issues in Femtocell Deployment in Broadband OFDMA Networks: 3GPP-LTE a case study" (2011) shows the benefits of the co-existence of macro/micro-cells and co-channel femtocells in OFDMA-FDD systems.

Femtocell systems are addressed in a broader manner in numerous research papers. Some of the relevant publications are: S. Hassan et al.'s "Femtocell versus Wi-Fi –A Survey and Comparison of Architecture and Performances" (2009), F. Meshkati et al.'s "Mobility and Capacity Offload for 3G UMTS Femtocells" (2009), and M. Khan et al.'s "Local IP Access (LIPA) Enabled 3G and 4G Femtocell Architectures" (2011). The latter describes several architectures for different LIPA scenarios. Trade off implications between capacity offload and UE battery life with regards to Femtocells in 3GPP UMTS are the subject of F. Meshkati et al.’s, “ Mobility and Capacity Offload for 3G UMTS Femtocells” (2009).

The similarities and differences between Femtocells and technologies such as Wi-Fi is the subject of S. Hassan et al.’s “Femtocell versus Wi-Fi–A Survey and Comparison of Architecture and Performances” (2009). This work states that both Femtocells and Wi-Fi can provide services based on the use of IP networks and that “evaluating their performances under the varied conditions of IP networks is an interesting area of future work.”

E. THESIS ORGANIZATION

Chapter I validated the need for this research by providing an overview of the purpose and relevance of this research. With its brief introduction and background to the subject of femtocells, Chapter I is intended to point out that there has been little research with regards to comparing femtocell and Wi-Fi capabilities and performance. The chapter also contains a literature review of relative femtocell research and concludes with a discussion of how this body of work is organized.

Chapter II presents a brief history of femtocell technology. Chapter II goes on to list several issues and challenges associated with femtocell deployment. These included quality of service, frequency/bandwith, interference, handover, regulatory, and security challenges and issues. The chapter goes on to describe basic femtocell and Wi-Fi architectures.

Chapter III presents a description of the methodology and experiments that will be conducted within this research. Chapter III began with establishing baseline testing in both ideal and non-ideal conditions. The chapter then goes on to describe testing in the areas of Internet accessing via HTTP, and downloading of various sized files, various sized RTP file streaming, and VoIP.

Chapter IV lists, describes, and summarizes the data collected in Chapter III. Chapter IV goes on to point out the key findings and the results of the tests performed in Chapter III.

Chapter V provides an overall conclusion to the research study. The chapter revisits the intent of the research to ensure that all objectives set forth were adequately addressed. The chapter concludes by highlighting recommendations and potential future research topics relating to this research.

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II. FEMTOCELL HISTORY, ISSUES, AND CHALLENGES

A. A BRIEF HISTORY OF FEMTOCELLS

The actual term femtocell is used to describe a coverage area, scale, or size. As shown in Figure 1, the macrocell is the largest level cell and it provides the widest range. The macrocell is found in most rural areas and can be located along major highways. The next smaller size cell is the microcell. It is used in very densely populated areas (mostly urban) like cities and large towns. Within these cells is the picocell, which is for areas that are even smaller. Picocells are often found in large office buildings, industrial areas, and commercial areas (i.e., shopping centers and malls). The smallest cell is the femtocell. Femtocells can be found in a person's home or an individual office.

Research into "small cells" can be found in literature as early as 1984. For instance, in his article "Small-Cell Mobile Phone Systems," Arthur Stockton describes systems that have "direct access to the land telephone network and are designed to connect any mobile phone to any other phone, mobile or not." In the 1990's there was increasing demand for cellular services and as a result the macrocells were being overloaded.

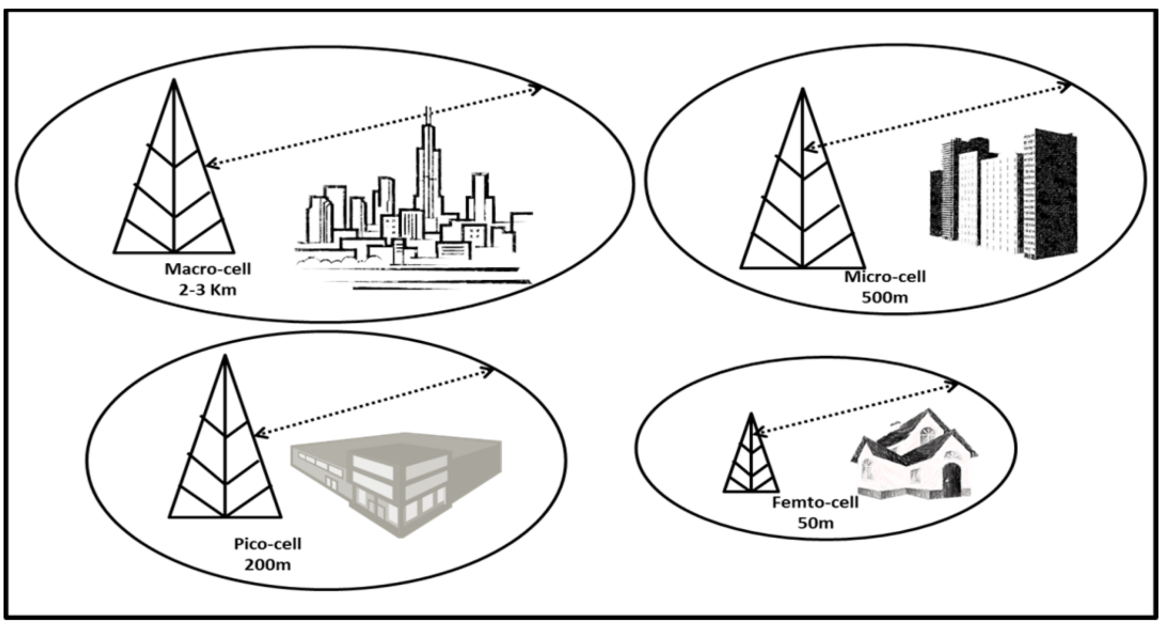


Figure 1. Macro-cell, micro-cell, pico-cell, and femto-cell ranges

This led to the development by Southwest Bell and Panasonic of a method of reusing the same frequencies as outdoor (macrocellular) cellular systems to provide wireless communications inside a building. This was accomplished by using a wired backhaul. Even though the technology wasn't quite there to support the IP backhaul and it was very costly, it was the first actual femtocell type network.

Over the last decade there has been a dramatic increase in consumer demand for increased capabilities through mobile means. According to Cisco Visual Networking Index (Cisco white paper: Forecast and methodology, 2011–2016), the amount of global mobile data traffic in 2011 has more than doubled for the fourth year in a row, and global mobile data traffic in 2011 was over eight times greater than the total global internet traffic in 2000. With this incredible growth, the need for new cellular architecture with greater capacity was necessary. Fortunately, the development of 4G standards that are based on Orthogonal Frequency-Division Multiple Access (OFDMA) and IP have provided a more efficient, low cost, platform for femtocells.

Current technology has introduced automatic configuration and self-optimization capabilities in femtocells making them user friendly and, ultimately, sold in a plug-and-play type product. They also have the ability to automatically integrate into macro-cellular networks. As a result, over the last four years major femtocell deployments by the biggest cellular companies in the world has occurred. Sprint, Verizon, AT&T, and others worldwide now offer femtocells compatible with their underlying radio-infrastructures.

B. FEMTOCELL ISSUES AND CHALLENGES

1. Quality of Service Issues

The term Quality of Service (QoS) refers to the requirements that are imposed by IEEE 802.11 on all aspects of an Internet connection. Some of these requirements are adequate signal-to-noise ratio (SNR), frequency responses, loudness levels, response time, loss, etc. The intent is to guarantee a standardized level of quality and performance for the consumer's data flow needs. The issue with QoS for femtocells is that in order to achieve QoS requirements there often needs to be hardware changes. A possible solution may be to use a traffic classifying service like Differentiated Services (DiffServ) or Integrated Services (IntServ). IntServ improves QoS by having applications use resource reservation protocol (RSVP) to improve requests and reserve resources through a network. DiffServ prioritizes packets according to the type of service they desire. Routers and switches can prioritize these to improve quality. WiFi, however, already must comply with IEEE 802.11QoS standards, and currently has established mechanisms in place to ensure QoS.

2. Frequency / Bandwidth Issues

The electromagnetic spectrum is a scarce and crowded resource. Femtocells operate on the same licensed spectrum that is allocated to cellular service providers. To deal with this overcrowding issue two methods have been used: the Co-channel Frequency Deployment and Orthogonal Channel Deployment. The Co-channel Frequency Deployment simply allows the femtocell and the cellular macro-cell to use the same frequency band. With co-channel use, however, there are identified interference issues. Orthogonal Channel Deployment is in many ways the opposite of Co-channel Frequency Deployment. In this method macro-cells and femtocells use separate channels. The advantage to this method is that there is less potential for interference, the disadvantage is a reduction in the overall system capacity.

WiFi networks use different Industrial, Scientific, and Medical (ISM) frequency bands. These unlicensed ISM bands are operated independently of any specific cellular service and are available for public use. This however may also lead to interference problems when too many WiFi devices are located near each other using the same band.

3. Interference Issues

As stated earlier, there is limited spectrum on which cellular systems can operate and the spectrum is controlled by licensing. Femtocells utilize the spectrum already licensed for cellular providers. Thus, interference is a key issue associated with femtocells. When multiple femtocell devices are being serviced by the same macro-cell there can be adjacent channel interference. There can also be interference issues when several femtocell devices are used in close proximity to each other, regardless of whether or not they are serviced by the same macro-cell. Generally though, femtocells are used in areas of poor or limited cellular coverage and in these cases interference from overcrowded networks is not an issue. Also, a benefit of the low power output of the femtocell is that multiple femtocell devices would have to be very close to each other to cause interference. WiFi devices can also face similar interference issues stemming from the fact that all the WiFi devices are working on the same unlicensed band, are often in the same vicinity as other WiFi access points or user devices, and use a very limited number of non-overlapping channels – specifically, three of the eleven available in the U.S. (of the twelve overseas). This latter fact impacts the utility of WiFi in congested areas.

4. Handover Challenges

When a mobile device in a WiFi network moves to the outer edge of its Received Signal Strength (RSS) limit it needs to perform a "handover" of connection from one access point to another. The major concern for femtocell handover is that the coverage area of an individual femtocell is very small. For this reason, it becomes essential that there is a seamless handover to and from femtocells so the user can maintain continuous signal connectivity. There are generally three types of handovers for both WiFi and Femtocells. The first is a simple base station to base station handover where a user moves from the range of one base station to another. The second occurs between base stations and Femto Access Points (FAPs).

The base station to FAP handover happens when the mobile user moves from an outdoor area to an indoor area. When the user starts outdoors it sends a request to a cellular base station and when the user then moves indoors the FAP will accept the request and pick up the signal. For this to work there has to be synchronization between the FAP and the cellular base station.

The final handover scenario is where the user moves from one FAP to another. This generally happens when there are multiple FAPs in the same vicinity, in an office building for example. The challenge associated with handovers for femtocells is that they are not usually connected to a network environment where mobility is addressed, (again as in an office building where mobility outside the building isn't a concern). Due to the fact that the femtocell must be associated with an IP address, whe a user is mobile the IP addresses would have to change.

5. Regulatory Challenges

One of the biggest differences between WiFi and femtocells is the fact that WiFi operates in an unlicensed spectrum while femtocells operate in a licensed spectrum and require regulatory approval. This becomes an issue because the spectrum and radio regulations will vary from one country to the next. International agreements can also be involved when a user takes their femtocell from one nation to another. In a licensed spectrum the provider pays substantial sums to be able to use a portion of the spectrum exclusively and regulators will enforce transgressions. This means that a femtocell operator could not just move their femtocell to another country and operate it. The varying spectrum allocations from one country to another can also prevent unauthorized usage.

A femtocell has several means to identify where it is. The first is a Global Positioning System (GPS) receiver that is built into the femtocell. This immediately identifies the location of the femtocell. Another means is by mapping its IP address to the femtocell's originating country. A femtocell also can sense other cell site identities in its area and can identify its "neighborhood." If a femtocell sees that it is in an unauthorized area it can disable itself or notify the provider.

Due to the regulatory issues operators cannot use their femtocells in frequency spectrum that they do not own and control. Some large providers (Verizon, AT&T, T-Mobile) may have operations in several different countries and therefore they license the spectrum in those countries. A femtocell user with one of these companies would still not be able to use their femtocell in these countries because the spectrum allocation may be different and the femtocell would still broadcast its original identity (trying to connect to its home network). Many femtocells have 2G and 3G receivers that can scan for signals from external cellsites and can determine the country in which it is located and what networks are available. The surrounding cellsite identities will change if the femtocell is moved. This could interfere with local mobile phone users who could possibly pick up the signal, and would also cause unnecessary hand-offs that would reduce signal strength.

6. Security Challenges

The security of a device or network is always a paramount concern for users, especially on a wireless medium. There are three major security vulnerability concerns for femtocell network technology. The first comes from the wireless link into the femtocell. According to a technical white paper from Picochip (2011), it is possible for external wireless transmissions to potentially gain unauthorized access to the femtocell. The second concern is the backhaul link that is used between the femtocell and the gateway into the service provider's core network (the Internet link). The third concern is the femtocell itself, as it is potentially possible for nefarious network users to get into the femtocell and take control of it remotely.

There are several ways to prevent or counter these security issues. The first is to ensure secure authentication. Authentication needs to be required by the service provider or the operator to correctly identify valid femtocells within the network. Another means of ensuring security is the use of Internet Protocol Security (IPsec). IPsec is a protocol for securing IP communications by authenticating and encrypting each IP packet. It also establishes mutual authentication and provides cryptographic keys for additional security. Extensible Authentication Protocol (EAP) is an authentication framework for wireless networks and also provides a means of ensuring wireless security.

C. BASIC FEMTOCELL ARCHITECTURE

A basic femtocell network architecture, as shown in Figure 2, is generally comprised of three elements: a Femtocell Access Point (FAP), a security gateway, and a femtocell management system. The FAP base station also requires a means of connecting to the Internet, typically through a broadband Internet connection (DSL, cable modem, or direct ISP access).

The Femtocell Access Point is basically a small scale cellular base station. It is the primary node in the network that connects the user to the network, and can be used in stand-alone or integrated configurations. When used in the stand-alone configuration the FAP is connected directly to the user's router, whereas in an integrated method the FAP has its own built-in router. A typical femtocell access point base station will transmit 100 mW of power, has a data rate of between 7.2 and 14.4 Mbps, operates at between 1.9 and 2.6 GHz, and has an effective range for high performance of approximately 100 feet (dependent upon location and interference issues). Note that this data rate is comparable to IEEE 802.3 10BASET connections (traditional "Ethernet").

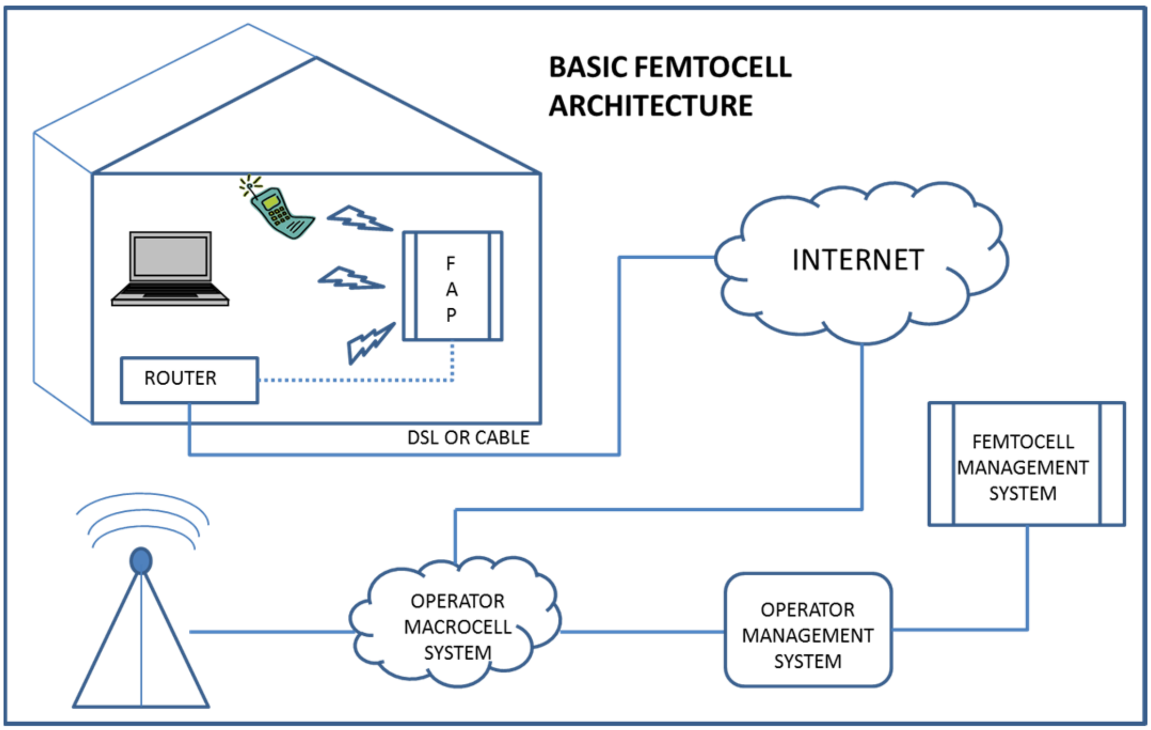


Figure 2. Basic femtocell architecture

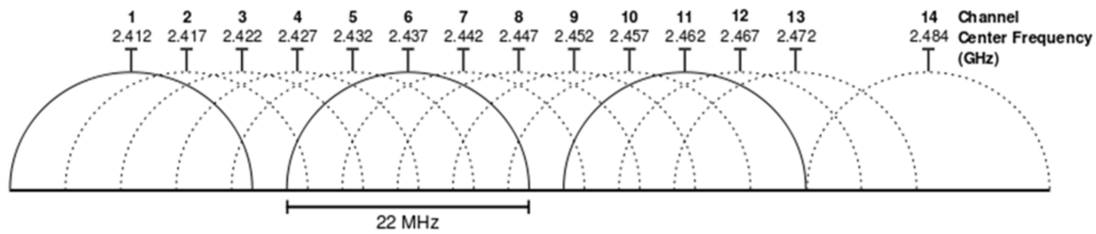
In all systems pertinent to operations and support, security is a very important issue. In a femtocell architecture the security gateway is a network node that provides a secure means to access the Internet. The security gateway uses Internet Protocol Security (IPSec) and Internet Key Exchange (IKEv2) Internet security protocols for encryption support and for the authentication and authorization of the femtocells. Femtocell security gateways are network nodes that have been designed for use in carrier-type networks and meet availability, scalability, and network management security requirements.

The femtocell management system is arguably the most important element in the femtocell architecture. A femtocell management system must comply with Technical Report 069 (TR-069), which is a protocol for communication between Customer Premise Equipment (CPE) and Auto-Configuration Servers (ACS) that encompasses secure auto-configuration as well as other CPE management functions within a common framework. The femtocell management system plays a critical role in the operational management, provisioning, and activation of the femtocells. It is the femtocell management system that allows the operator to control the device remotely ensuring that it is in compliance with local regulations.

For Internet connectivity, femtocells connect to the mobile operator's network via a standard broadband connection, such as DSL, fiber, or cable. The data to and from the femtocell is carried over an IP technology-based network provided by an Internet Service Provider. For wireless (mobile device) users, the connection to the femtocell is done via the normal cellular service technologies just as if they were using a conventional macro-cellular network to connect.

D. BASIC WI-FI ARCHITECTURE

A wireless local area network (WLAN) is a collection of wireless devices that will maintain connectivity with each other while transferring data. The WLAN works in three basic configurations: peer-to-peer, bridge, and wireless distribution system. Peer-to-peer configuration is where each computer in the network can act as a client or server for the other computers in the network. This allows them shared access to files (such as audio, video, data, etc.) and peripherals without needing a central server. A bridge configuration is used to connect networks. This is done by use of a wireless Ethernet bridge, providing the connection for devices to a wireless network. The wireless distribution system enables the wireless inter-connection of the access points within a network. This allows a wireless network to be expanded through the use of multiple access points linked together. Generally, a WLAN's signal can reach to 500 feet indoors and approximately 1000 feet outdoors. WiFi operates in the unlicensed 2.4 GHz or 5.8 GHz ISM Band. WiFi transmissions are essentially FM transmission, in that the frequency is changed to transmit data. The 2.4 GHz spectrum is shown in Figure 3.



2.4 GHz Wi-Fi channels (802.11b,g WLAN) (Gauthier, Michael, Wireless Networking in the Developing World, 2009)

Figure 3. 2.4 GHz Wi-Fi channels from Gauther, M., Wireless networking in the developing world (2009)

WiFi is a limited range wireless networking protocol based on the IEEE 802.11 standards. Having WiFi connectivity allows a user to transfer data at the speed of broadband using radio waves rather than a wired or cabled infrastructure. A short-range wireless network (often referred to as a WiFi network or Wireless Local Area Network (WLAN)) is set up by using radio signal frequency to communicate among computers and other wireless-enabled devices. The main architectural components of a wireless network are the wireless router (access point), WiFi cards, safeguards, and one or more wireless clients. In simplest terms, an Access Point (AP) is a wireless LAN transceiver, or “base station,” that can connect one or many wireless devices simultaneously to the Internet. WiFi cards are installed in client devices and accept the wireless signal and relay information. Safeguards are firewalls or anti-virus software products that protect networks and help to keep information secure.

As shown in Figure 4, the basic WiFi architecture starts with a station. This is essentially a computer that can be either mobile or fixed. A Basic Service Set (BSS) is created when two or more stations come together in order to communicate with each other. According to IEEE 802.11, there are two types of operating modes: infrastructure mode, and ad hoc mode. Infrastructure mode is used to connect a computer with a wireless network adapter (or wireless client) to a wired network. This is accomplished through a wireless router or access point. Ad hoc mode is used to connect wireless clients directly together. This method does not use a wireless router or access point. The ad-hoc network refers to when a BSS is not connected to an Internet interface device and it is then referred to as an independent BSS (IBSS).

When two or more basic service sets need to be connected it is done through a Distribution System (DS). The DS increases network coverage by allowing the wireless network to be expanded using multiple access points without needing a wired backbone to link them.

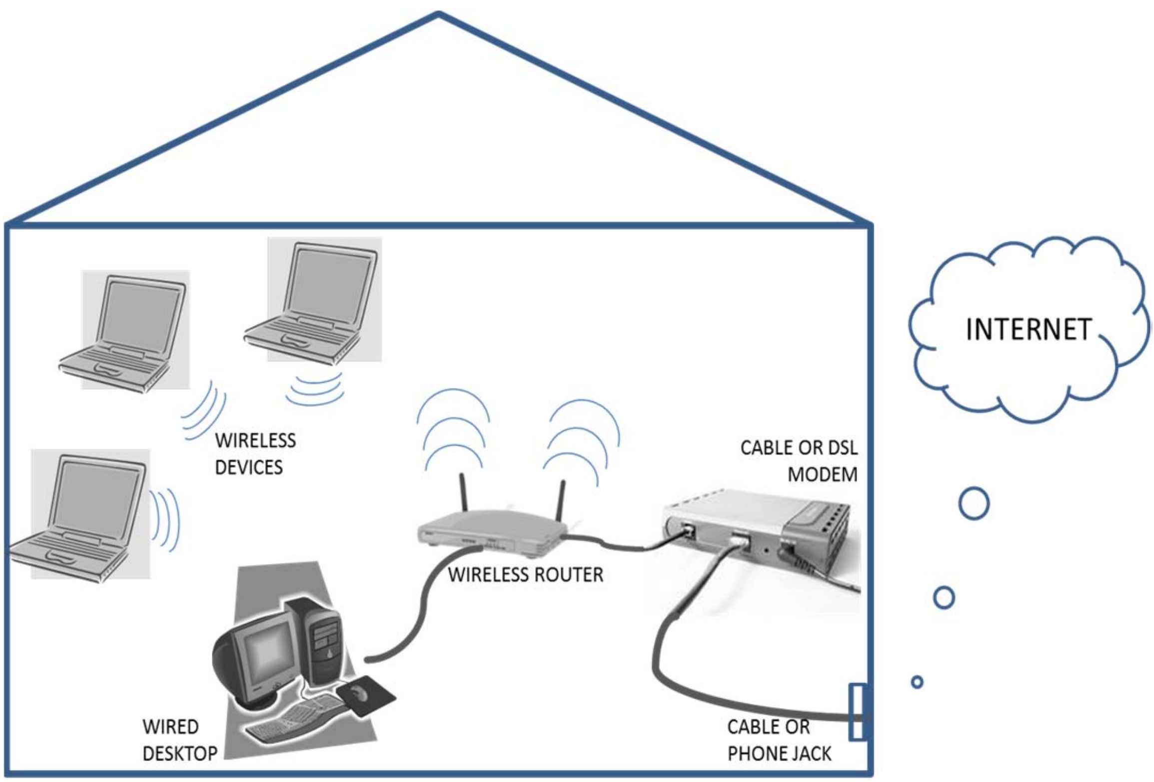


Figure 4. Basic Wi-Fi network

In this chapter we discussed the functionality of femtocells, and introduced the reader to some of the prevalent issues and challenges of femtocell technology. These items need to be resolved for the femtocell to be an accepted and widely used technology.

The key is to ensure that femtocells are scalable, and easily integrated. Femtocells also must be robust enough to successfully deal with security, regulatory, and interference issues. This chapter ended with a basic description of both femtocell and WiFi architectures. With a basic understanding of the history, issues, and architecture of femtocells we now turn to the purpose of this work, which is to compare and evaluate the performances between femtocells and WiFi networks.

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III. METHODOLOGY

A. INTRODUCTION

The approach to this work is directly linked to the purpose, objectives, and scope listed in Chapter I. There is currently very little research published specifically developing an analysis of Femtocell versus WiFi in terms of their respective performance and capabilities. In this chapter, we provide the methodology for the tests and extensive experimentation conducted with respect to these technologies.

Our research includes numerous testing tools that provide multiple measurements. These are evaluated and compared as to suitability for the experiments conducted herein. To compare the performances between Femtocell and WiFi, we must start first with a stable environment where the testing can be repeated with no outside interference nor variation. In our study, we use a single laptop computer that functions as a client. The laptop is alternately connected to the Internet through either a router and a Femtocell or a wireless router alone. When using the Femtocell, the laptop is connected to the Internet via a mobile hotspot provided by a cellular “smart” phone.

Femtocells are base stations that, by design, connect automatically to a cellular mobile operator network. This internal connection process renders it impossible to manually create and manipulate your own network. Thus, due to its server-client architecture, communication among devices directly through the femtocell is not possible and can only be accomplished through the transfer of data from the client, to the network, and through the server. Due to these facts, we chose to use a single laptop computer as a client with both access to a Wi-Fi router and a mobile hotspot. As this is how a mobile phone accesses the Internet this is actually beneficial for our research, as it provides a more realistic environment for testing.

B. TECHNICAL SPECIFICATIONS

The devices used in this research can be described as micro-environmental devices. This means that they are all located indoors and are purchased, owned and operated by the average Internet user. They include a wireless router (802.11 wireless access point), a Femtocell (Verizon Network Extender), a Motorola Droid RAZR 4G cellular phone (with its mobile hotspot enabled), and network endpoints (client and server nodes). A comparison of the general specifications for Wi-Fi and Femtocells can be seen in Table 1.

	Wifi	Femtocell
Data Range Capabilities	11 and 54 Mbps	7.2 – 14.4 Mbps
Operating Frequency	2.4 and 5 GHz	1.9 – 2.6 GHz
Power Output	100, 200 mW	10, 100 mW
Range	100 – 200 m	20 -30 m
Services Provided	Voice & Data	Voice & Data

Table 1. General Wi-Fi femtocell specifications

1. Wireless Router

A wireless router is a device that provides wireless signals for connecting network devices that have wireless adapters (Table 2). The purpose of the wireless router is to send wireless signals that can be interpreted by the wireless-enabled network clients for communicating data and information. Routers collect signals and convert them into wired signals and send them over the Local Area Network (LAN). A wireless router will generally have a 20 – 30 meter indoor range and approximately 80 – 100 meter outdoor range. Routers can usually connect several wireless devices within their area of coverage.

Model	Netgear WGR614 (v7)
Frequencies:	2.4 – 2.5 GHz
Network Speed/Data Rates:	54 Mbps
Antenna:	2 dBi
Encryption:	64 bit, 128 bit, and 152 bit, WEP encryption, WPA (WiFi Protected Access)
Data and Routing Protocols:	TCP/IP, RIP-1, RIP-2, DHCP, PPP over Ethernet (PPPoE)
Interface Specifications:	LAN: 10BASE-T or 100BASE-Tx, RJ-45 WAN: 10BASE-T or 100BASE-Tx, RJ-45
Data Encoding:	802.11b: Direct Sequence Spread Spectrum (DSSS) 802.11g: Orthogonal Frequency Division Multiplexing (OFDM)

Table 2. Wireless router specifications from Netgear Support www.Netgear.com

2. Femtocell

The femtocell is a small cellular base station that is designed for use in small areas, like homes and buildings (Table 2). It works by connecting to a service provider's network through broadband networks (DSL or cable). Femtocells have a range of 20 – 30 meters, and can generally support up to six devices. A comparison of all commercially available Femtocells is provided in Figure 5. For our testing we will be using the Samsung Wireless Network Extender provided by Verizon (Table 3) connected directly to the wireless router via an Ethernet cable.

Carrier	AT&T	Verizon	Sprint	T-Mobile
Solution	Femtocell - "3G MicroCell"	Femtocell - "Network Extender"	Femtocell - "Airave"	UMA - "HotSpot@Home"
Branding	Cisco	Samsung	Samsung	NA
Technology	3G UMTS/HSPA for voice and data	2.5G CDMA 2000 1xRTT	2.5G CDMA 2000 1xRTT	UMA voice over WiFi
Simultaneous Calls	4 Simultaneous	3 Simultaneous	3 Simultaneous	NA
Standby Approved Callers	10	100	50	NA
Data Bitrate	3.6 megabits/s (HSDPA 3.6)	144 kilobits/s	144 kilobits/s	NA
GPS Fix Required	Yes	Yes	Yes	NA
Hand-On/Hand-Off	No/Yes	No/Yes	No/Yes	Inter AP Handover/Yes
Coverage	5000 square feet	5000 square feet	5000 square feet	WiFi AP range

Figure 5. Femtocells; A comprehensive exploration, www.anandtech.com, from Brian Klug (4/1/2010)

Model	Samsung Wireless Network Extender (SCS-2U01)
Frequencies:	800/1900 MHz
Air Interface:	CDMA2000 1x Rel 0 CDMA2000 EvDO 0/A
Traffic Channel:	Up to six simultaneous users (a seventh is reserved for emergency calls)
Transmission:	10/100 Base-T Ethernet/Network
Standards:	IEEE 802.3, IEEE 802.3u for Ethernet IEEE 802.11g, IEEE 802.11b for Wireless
Power Range:	10 mW to 30 mW

Table 3. Samsung wireless network extender femtocell specifications

3. Cellular Smartphone

In this research, we use a Motorola Droid RAZR cellular phone with the Mobile Hotspot application enabled with the specifications found in Table 4. The Motorola Droid RAZR is a 4G capable LTE smartphone that has a built in Mobile Hotspot application. A mobile hotspot is a means of allowing the mobile phone to act as a Wi-Fi access point, providing a network access to nearby computers, Tablets and other Wi-Fi capable devices. The Motorola Droids mobile hotspot application allows the phone to connect to a mobile data network and then act as a Wi-Fi router, distributing the bandwidth to nearby clients. Any Wi-Fi enabled computer or mobile device can connect to the network that the mobile hotspot provides. A significant advantage to the mobile hotspot provided by the Droid RAZR is that it is completely mobile. The cellular phone receives its signal through the nearest macro-cell station. Using this method, however, requires the user is in the provider's area of coverage. The connection speed provided by the mobile hotspot depends on many variables, including the cell network to which you are connecting, how far you are from the network's closest transmission tower and how congested the shared service may be at the time. A typical cellular phone mobile hotspot has a range of approximately 100 feet.

Model	Motorola Droid RAZR XT912
General:	2G GSM 850/900/1800/1900 CDMA 800/1900 3G HSDPA 850/900/1900/2100 CDMA2000 1xEV-DO 4G LTE 700 MHz Class 13-For Verizon
Memory:	16 GB storage, 1 GB RAM
Data:	GPRS: Class 12, 32–48 kbps EDGE: Class 12 Speed: Rev. A, up to 3.1 Mbps, LTE, HSDPA, HSUPA WLAN: Wi-Fi 802.11 b/g/n, DLNA, Wi-Fi hotspot Bluetooth: v4.0 with LE+EDR
Operating System:	Andoid OS, v4.0.4 (Ice Cream Sandwich)
Browser:	HTML, Adobe Flash
CPU:	Dual-core 1.2 GHz Cortex-A9
Chipset:	TI OMPA 4430
Java:	Via Java MIDP emulator
GPS:	With A-GPS support

Table 4. Droid RAZR XT912 specifications

4. Network Endpoint

A network endpoint is a device that enables a user to access network services. In this research we use the Motorola Droid RAZR and a Hewlett-Packard laptop computer as seen in Table 5. The Droid RAZR will create a mobile hotspot, and the HP laptop will alternately utilize the created hotspot network and the router created Wi-Fi networks to run the tests needed to measure and compare the performances and capabilities of the two technologies.

Model:	Hewlett-Packard HP G62 Notebook PC
Microprocessor:	2.50GHz VISION Technology from AMD with AMD Turion II Dual-Core Mobile Processor N530
Memory:	4GB DDR3 System Memory (2 DIMM) 8MB (max memory)
Video Graphics:	ATI Mobility Radeon HD 4250 Graphics
Video Memory:	Up to 1917 MB
Hard Drive:	320 GB (5400RPM)
Network Card:	Integrated 10/100 Ethernet LAN
Wireless Connectivity:	802.11 b/g/n WLAN
Operating System:	Windows 7 Home Premium 64-bit

Table 5. Network endpoint specifications

C. TESTING

The ultimate goal of this research is to evaluate the utility of Femtocells by comparing their performance to that of a traditional wireless Wi-Fi network. To accomplish this, our research evaluated the performance and capabilities of these two technologies through several use-cases, applications, and scenarios. Our research performed baseline tests and assessment of the basic performances of these two technologies in ideal conditions. These tests are described below. We then transitioned to a realistic environment evaluation. The realistic environment tests were conducted in less than ideal settings that involve both line-of-sight obstacles and distance from the access point or femtocell. Support for Internet applications, such as browsing or “surfing” through HTTP protocol, RTP protocol applications for streaming, and transfer of audio/video files was also conducted. Finally, we evaluated the VoIP supporting protocols offered by both Femtocell and Wi-Fi provisioned networks.

1. Testing terms

Ping is basically the process of sending an echo-request packet from the user's computer to a different or remote computer (or server). The time between the transmission of the request (or ping) and the receipt of the associated echo-reply is a measurement of the latency of the connection. Ping is measured in milliseconds (ms). If the user experiences a delayed response in Internet applications it could be due to a higher than desired network latency. Latency is a term that basically means the delay during the performance of a given operation. Latency is used to describe any type of delay that occurs during the transmission or processing of data packets, such as transmission, propagation, processing, or queuing.

Jitter is the variance in measuring successive ping tests. A reading of zero in a *jitter* test means that the results were exactly the same every time. A score above zero indicates the amount by which they varied. The lower the jitter value the better the connection service quality for applications sensitive to delay.

Packet Loss is the term used to refer to unsuccessful transmission of "packets" of data. Having packet losses usually means that there is a deficiency associated with your Internet connection. Losses of packets may reduce upload and download efficiency, particularly due to requirements for retransmissions by applications sensitive to packet loss, lead to poor quality VoIP audio, and pauses in streaming media. Packet loss, generally associated with network congestion and its inherent packet collisions on wireless links or queue-overloads, is a metric where anything greater than zero percent may be an issue.

Packet Order is a measure in percentage of how many packets arrived in order. Packets do not necessarily take the same route or the same time to reach their destinations. This results in packets arriving out of order, which causes other packets to be delayed or discarded. Delayed or discarded packets may cause a performance problem for the application, and as noted above, may lead to increased retransmissions which exacerbate the network performance issues.

Packet Discards is a measure of packets that arrive too late to be used by the application. Packet arrivals may be very time sensitive, especially with respect to media-based applications, such as audio or steaming-video. If a packet arrives too late the application performance suffers, and the packet has to be intentionally discarded, effectively wasting the network resources used to deliver it.

A *Mean Opinion Score* (MOS) is a measure from 1 (being the worst) to 5 (being the best) as a rough order of service quality. MOS originated from the phone companies and used human input from related quality tests. Software applications have adopted the MOS score and scale. MOS scoring can be described as follows: 5 – Clear, as if in a real face-to-face conversation; 4 – Fair, small interference but sound is still clear; 3 – Not fair, enough interference to start to annoy the user; 2 – Poor, very annoying and almost unusable; 1 – Not fit for purpose.

Download/Upload Speed– more appropriately referred to as rate - is a measurement of how fast a user's connection can deliver content to/from their computer. Note that this is generally a relative measure and not the theoretical value for the link. It must also be specified whether the value refers to the consolidated rate for the link or the effective rate for individual hosts. For example, the upload speed of a satellite link may be 1.5 Mbps; however, that capacity is shared among all users accessing that link. Thus, if 20 users are concurrently accessing the link, each may only receive 75 Kbps of service. When collecting data pertinent to upload or download rates, one must be cognizant of the user population.

To achieve the optimal delivery of information for applications like VoIP, email, and on-line interactive programs, the receiving party's download rate must be at least as fast as the sending party's upload rate. In most cases uploading files is slower than downloading files. This is due to the fact that most Internet connection devices are asymmetrical. This means that they are designed to provide better downloading rates than upload rates. The reason for this is that most users spend the majority of their time on the Internet viewing web pages or using multimedia files which involve downloading. For this reason, the average uploading rate is typically much slower than the average downloading rate.

Round Trip Time is the time it takes for a packet to be sent end-to-end between the client and the server and for a response to be received back from the recipient. A long round trip time will dramatically slow connection throughput performance, particularly for TCP-based applications, and an erratic round trip time is an early indication of congestion problems.

2. Baseline Testing

The baseline tests performed in this research were conducted to establish preliminary network parameters in ideal settings. These tests addressed parameters such as: bandwidth, download and upload rates, packet losses and transfers, signal strength, ping, and jitter. These tests were performed first to ascertain the best-case values that are achievable. These tests also identify where major differences between Femtocells and Wi-Fi exist. The assumptions we make for the baseline testing are, first, that we have an ideal channel that does not have any imperfections, interference, or delays; and, second, that the transmission and reception of the data takes place within normal traffic conditions.

To perform the baseline tests we utilized three open-source software tools. These included Pingtest.net, Speedtest.net, and Ping-test.net. Pingtest.net is an online performance-measuring tool that determines the quality of the user's broadband Internet connection with respect to latency. It does this through the measuring of round-trip-time, jitter, and packet loss. This tool also gives an overall grade of the user's broadband quality. Speedtest.net is also an online performance-measuring tool that tests the users Internet connection bandwidth with respect to upload and download capabilities between the assessed client and a remote server hosting the Speedtest application. Finally, Ping-test.net tests the performance of a user's Internet connection by checking how fast the user can download and upload data. It accomplishes this by sending both large and small packets of information through the Internet connection and measuring the speeds of their travel. This tool also addresses latency by measuring the round-trip-time time.

3. HTTP Web Access Testing

Hypertext Transfer Protocol (HTTP) is a stateless, application-layer protocol used to transfer data on the Internet. Web browsers and servers exchange information in accordance with the rules of HTTP. HTTP is a request/response protocol, which means that a web browser will initiate a request to a server and the server in turn sends a response, thus providing an information "pull" service. HTTP is used for every web page access and is used in every action involved in Internet "web surfing."

As HTTP is the underlying protocol used by the World Wide Web, it is very important to our research. Our testing addresses HTTP downloading and points out the differences between the capabilities of Wi-Fi and cellular in terms of downloading data from the Internet. We also consider the differences between the way femtocell and Wi-Fi access the Internet.

To address these areas, we use an open source tool entitled "Downtester." Downtester assesses Internet download speeds from multiple locations throughout the world. It allows the user to choose URLs and systematically tests the download speed of each. For this research, we chose the following six URLs: http://www.google.com, http://www.facebook.com, http://www.yahoo.com, http://www.baidu.com, http://www.youtube.com, and http://www.cnn.com. We also use Downtester to measure the time to download files of varying sizes. We specified test files that are 20 MB, 50MB, 100MB, and 200MB in size. We hold that these sizes represent the average users download needs. A 20MB file is considered a small file, equivalent to a standard-quality movie trailer download. A 50MB file is considered a medium sized file, equivalent to an MP3 audio CD download. The 100MB file is also considered a medium sized file, but it would equate to a high-quality MP3 audio CD download or a 2 minute high definition movie trailer. The 200MB file is a large file that would represent approximately 45 minutes of a video stream or a large operating system update.

Finally, we also use HTTP Analyzer, which is a tool that allows the user to monitor, trace, and analyze HTTP traffic in real-time.

4. RTP Streaming Testing

To test streaming capabilities we utilize Real-time Transport Protocol (RTP) and Real-time Transport Control Protocol (RTCP). These protocols provide end-to-end network transport functions for applications transmitting real-time data, such as interactive audio and video. Using RTP/RTCP, we can analyze videos of different sizes by using a packet sniffer program. Utilizing a packet sniffer program and a streaming video player, we can analyze the stream for information, such as sequence errors, jitter, packet losses, etc. This will provide a comparison between the performances of Femtocells and Wi-Fi for streaming video content.

To perform these tests we use the packet analyzing freeware program Wireshark. We use various size video files (20MB, 50MB, and 100MB) to stream through the VideoLAN Client (VLC) player. While streaming, we use Wireshark to capture packets for analysis.

5. VoIP Tests

Voice Over IP (VoIP) is voice communications delivered using Internet Protocol. This means sending voice information in digital form in discrete packets over packet-switched networks rather than the traditional switched-circuit sessions used in Public Switched Telephone Networks (PSTN). In these tests we analyze the differences between a Wi-Fi based connection and a Femtocell based connection. It is generally accepted that the better the upload/download speed the better the connection during a VoIP call. In the case of VoIP, jitter and packet loss are also factors for good quality.

To perform these tests we use two open-source online testing programs, VoIPreview.org/voipspeedtester and myspeed.visualware.com. VoIPreview is an online program that evaluates the parameters of a VoIP phone call. Myspeed.visualware.com is an online program that provides the calculations of all parameters necessary for a successful VoIP call and establishes the value for an all-encompassing Mean Opinion Score (MOS) this is shown in Table 6. This score is a quality-based score as introduced above. These values are not always presented in whole numbers; certain limits or thresholds are expressed in decimal form. The range of 4.0 to 4.5 is generally accepted as the level that provides a quality VoIP call. In contrast, values below 3.5 are considered unacceptable.

1	Impossible to communicate.
2	Very annoying. Nearly impossible to communicate.
3	Annoying
4	Fair. Imperfections can be perceived, but sound still clear. This is the range for cellular phones.
5	Perfect. Like face-to-face conversation or radio reception.

Table 6. Mean Opinion Score (MOS)

D. TESTING CONFIGURATIONS

In order to provide the viable comparison between Femtocells and Wi-Fi in terms of their respective capabilities and performance, we must examine how they function in two different configurations. Due to the fact that Femtocell devices cannot provide Internet connectivity by themselves, ad hoc networks needed to be created. In our research two ad hoc networks were created for testing and comparison purposes. The first configuration is the traditional wireless network consisting of a laptop accessing the Internet via a wireless router (Figure6). This configuration is then compared to the second configuration that utilizes the Femtocell. In this second configuration, the Femtocell utilizes the routers internal Ethernet switch to provide Internet connectivity to the Motorola Droid RAZR cellular phone (Figure 7). The Droid in turn, provides a mobile hotspot that allows the wireless laptop to access the Internet.

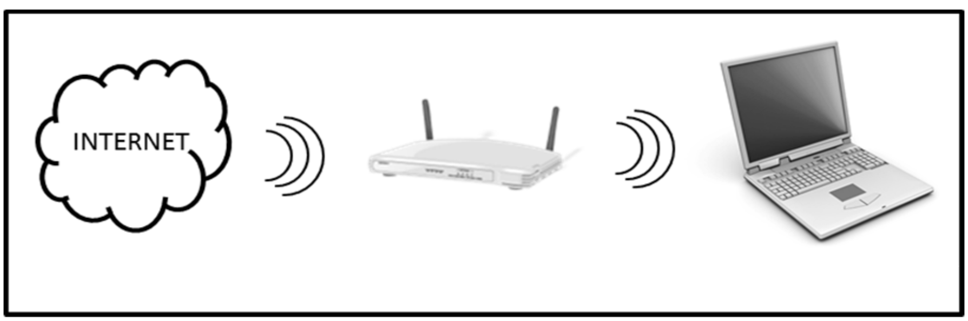

Figure 6. Internet to wireless router to wireless laptop

In this configuration, tests performed will be conducted with a traditional wireless network utilizing a wireless laptop.

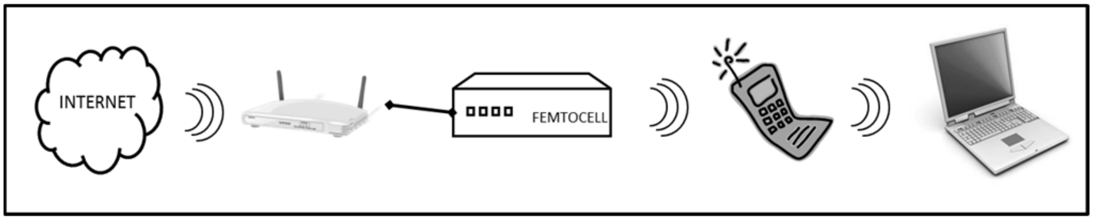

Figure 7. Internet to wireless router to femtocell to cellular mobile hotspot to wireless laptop

In this configuration, the Femtocell utilizes the wireless router (via an Ethernet cable) to provide Internet connectivity to the Motorola Droid RAZR. The Droid RAZR uses this to then provide a mobile hotspot that is used by the wireless laptop to access the Internet.

In this chapter we have provided the methodology for the testing and extensive experimentation that we will be conducting with respect to these technologies. We discussed the technical specifications of our devices, and briefly discussed the applicable testing terms that will be used during our testing. We have also described each of the areas where we will be testing the capabilities and performance of the Femtocell and the Wi-Fi devices. In our next chapter, we will begin our testing. We will first establish a baseline evaluation of both devices and utilize this information to compare the results of further testing in the areas of HTTP web accessing, RTP video streaming, and VoIP applications.

IV. TESTING AND RESULTS OF TESTING

A. BASELINE TESTING

1. Introduction

The baseline tests performed in this research were conducted to establish preliminary network parameters in near ideal settings. These tests address parameters such as: bandwidth, download and upload speeds, packet losses and transfers, signal strength, round-trip-time (RTT), and jitter. These tests must be performed first to ascertain the best case values that are achievable by each respective technology. These tests will also identify where the major differences between Femtocells and Wi-Fi exist. In this testing, we must assume that we have an ideal channel that does not have any imperfections, interference, or delays. We must also assume that the transmission and reception of the data takes place within normal traffic conditions. Testing under field-like conditions followed the baseline tests. Performance was measured using the three on-line tools described in Chapter 3. These included speedtest.net ping-test.net, and pingtest.net. The results of the tests are presented below.

2. Baseline Test Evaluation

The baseline tests results are relatively consistent in each of the respective tests. The averages are also what we expected from the selected equipment. These results are also in accordance with what we would expect from compliance with the 3GPP Femtocell standards and IEEE 802.11.

Wi-Fi uses the same frequency channels for their uploading and downloading operations. It does this by utilizing the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. This protocol is designed to provide fair access to the shared channels so that all stations get a chance to use a network (Liqiang, 2011). After every packet is transmitted, all stations use this protocol to determine which station gets to use the channel next. This process can however slow transmission rates. As shown in Tables 7 through 9, and Figures 8 and 9, the results of our baseline testing with the Wi-Fi router is a download average speed of 18.87 Mb/s. The results of our baseline testing with the Wi-Fi router is an average upload speed of 4.08 Mb/s.

Scenario	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
Wi-Fi	25	18.87	4.08
Femtocell	50.9	8.06	0.72

Table 7. Speedtest.net test averages

Scenario	Large Packet Ping	Small Packet Ping	Average Packet	Download Speed (Mb/s)	Upload Speed (Mb/s)
Wi-Fi	54.7	52	53.2	14.50	3.30
Femtocell	664.5	166.7	415.4	9.64	0.62

Table 8. Ping-test.net test averages

Scenario	Packet Loss	Ping	Jitter	Score
Wi-Fi	0	24.9	6.6	4.39
Femtocell	0	48.9	11.3	4.37

Table 9. Pingtest.net test averages

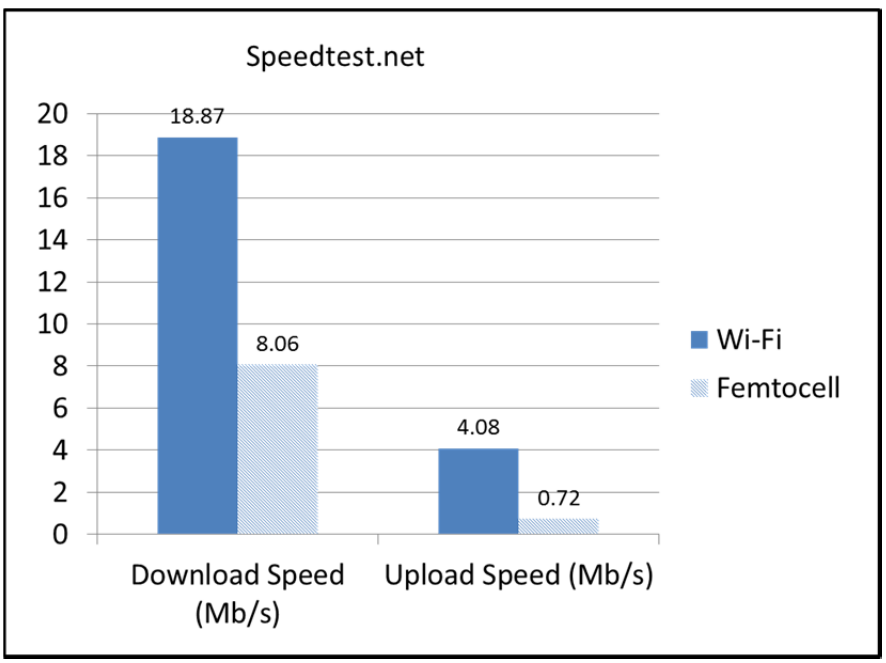

Figure 8. Speedtest.net results

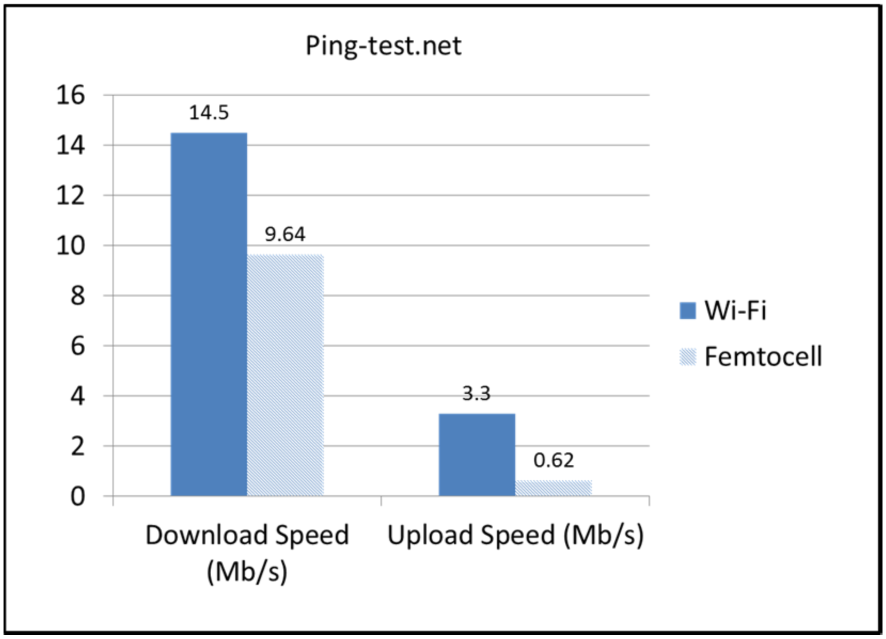

Figure 9. Ping-test results

Femtocells operate differently than Wi-Fi routers in that they have different frequency channels for both download and upload operations (Lopez-Perez, 2008). Since these are independent of one another you cannot compare them in the same way as Wi-Fi upload and download speeds. In Wi-Fi you simply add the download and upload speed averages and get a basic speed. For Femtocells you keep the upload and download separate and measure their capacity independently. As shown in Tables 7 through 9, and Figures 8 and 9, the results of our baseline testing show a download average speed of 8.06 Mb/s. The results of our baseline testing show the upload speed average of 0.72 Mb/s (720 Kbps).

In terms of basic speed the Wi-Fi's downloading speed is more than twice as fast as the Femtocell's downloading speed. For uploading operations the Wi-fi is more than five times faster. Downloading and uploading speed is not the only place where Wi-Fi outperforms the Femtocell, packet transmission time is also an issue. This can be seen by our next results in the measurements of ping delay (latency) data.

Ping is a measurement of the RTT of a packet of information to its destination and back. This includes moving through the Wi-Fi or Femtocell up-link and down-link as well as the infrastructure. If you were to assume that the delay in ping only came from uploading and downloading values then the Femtocell ping delay should be five times longer than the Wi-Fi ping delay. The tests results however showed a ratio of between seven and eight.

A possible reason for this is that the Femtocell has a more complex architecture. It has added steps to the process of achieving Internet connectivity. It must first move through the mobile operator's domain and then obtain access to the IP network. These steps lead to a larger delay in transit time. This is an additional "operating difference" that needs to be considered when evaluating which of the two technologies is more efficient.

Our last area to examine is the jitter results. As jitter is the amount of variance in successive ping tests the lower the value the better the connection. In our tests Wi-Fi jitter averaged 6.6ms (Table 14) and the Femtocell averaged 11.3ms (Table 15). There is not as much of a disparity between these scores, which may suggest that Femtocells tend to be slower in communications but can ultimately maintain a stable steady transmission.

Also of note on our Pingtest.net testing is the overall score rating (Tables 14 and 15). Pingtest.net gives a Mean Opinion Score (MOS), which is an indication of the overall quality of the connection. The MOS ranges from 1 to 5 with 1 being the worst and 5 being the best. The MOS score provided by this tool is comprised using an algorithm based on the three test components to estimate the connection quality. Tables 14 and 15 show the MOS results and with a score of 4.39/5 for Wi-Fi, and 4.37/5 for Femtocell both are given grades of A (rated as excellent).

3. “Speedtest.net” Upload/Download Test Results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	24	16.11	4.08
2	25	19.24	4.20
3	24	19.14	4.15
4	24	19.17	4.20
5	25	19.27	4.17
6	25	19.14	4.15
7	25	19.60	4.17
8	24	19.16	4.20
9	25	19.28	4.16
10	25	18.60	4.17
Average	24.6 ms	18.87 Mb/s	4.08 Mb/s

Table 10. Wi-Fi via router connection results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	55	10.21	0.18
2	41	11.85	0.35
3	55	12.80	1.21
4	65	2.13	0.49
5	38	6.63	1.12
6	45	13.94	1.46
7	45	7.90	1.02
8	55	1.51	0.38
9	55	11.44	0.68
10	55	2.18	0.29
Average	50.9 ms	8.06 Mb/s	0.72 Mb/s

Table 11. Femtocell connection results

4. Results of Ping, Jitter and Packet Loss Utilizing "Ping-test.net" and "Pingtest.net"

Test Number	Large Packet Ping (ms)	Small Packet Ping (ms)	Average Latency (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	56	56	56	11.38	3.5
2	53	53	53	17.06	3.36
3	54	51	52	13.96	3.3
4	56	50	53	13.95	2.14
5	50	54	52	13.71	3.72
6	57	54	55	16.31	3.76
7	57	50	53	14.13	3.14
8	53	51	52	14.61	3.37
9	56	51	53	15.21	3.37
10	55	50	53	14.69	3.29
Average	54.7 ms	52 ms	53.2 ms	14.50 Mb/s	3.30 Mb/s

Table 12. Wi-Fi connection Ping-test.net results diagram

Test Number	Large Packet Ping (ms)	Small Packet Ping (ms)	Average Latency (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	206	87	146	5.64	0.16
2	1478	119	798	10.84	0.05
3	646	490	568	1.73	0
4	1490	254	872	0.84	0
5	1873	339	1106	4.73	0
6	167	73	120	13.40	0.75
7	191	87	139	14.93	1.14
8	227	74	150	14.25	1.43
9	117	74	95	15.36	1.19
10	250	70	160	14.64	1.48
Average	664.5 ms	166.7 ms	415.4 ms	9.64 Mb/s	0.62 Mb/s

Table 13. Femtocell connection Ping-test.net results diagram

Test Number	Packet Loss (%)	Ping (ms)	Jitter (ms)	Score (# out of 5)
1	0	23	6	4.39
2	0	36	12	4.37
3	0	21	2	4.39
4	0	26	10	4.38
5	0	27	11	4.38
6	0	24	7	4.39
7	0	27	10	4.38
8	0	21	2	4.39
9	0	24	5	4.39
10	0	20	1	4.39
Average	0 %	24.9 ms	6.6 ms	4.39/5.0

Table 14. Wi-Fi connection Pingtest.net results diagram

Test Number	Packet Loss (%)	Ping (ms)	Jitter (ms)	Score (# out of 5)
1	0	61	21	4.35
2	0	44	6	4.38
3	0	51	13	4.36
4	0	46	6	4.37
5	0	44	7	4.37
6	0	50	14	4.36
7	0	51	15	4.36
8	0	47	10	4.37
9	0	46	8	4.37
10	0	49	13	4.36
Average	0%	48.9 ms	11.3 ms	4.37/5.0

Table 15. Femtocell connection Pingtest.net results diagram

B. BASELINE TEST IN REALISTIC ENVIRONMENTS

1. Introduction

We established a baseline set of tests and results in ideal conditions. These results will be useful as reference points for successive testing. As most users of both Wi-Fi and Femtocell technology will be utilizing them in less than ideal settings we now need to obtain test results in realistic environments.

2. Software Used

WiEye is a freeware 802.11 Wi-Fi analyzer application for the Android smartphone. WiEye is used for wireless site surveys, Wi-Fi scanning, and wireless discovery. It displays the name, Basic Service Set Identification (BSSID), channel, and frequency of any access points within range. This application can also graph this data to evaluate Wi-Fi congestion for each available channel. (http://www.WiEye.net) In our research we will be utilizing this application to test the frequency strength in our various scenarios.

OpenSignalMaps is a freeware Android application that allows the user to map the location of the tower to which the cellular phone is connected, test the connection speed, measure the exact signal strength, and provide a graphical depiction of average signal strength over a period of time.

Xirrus Wi-Fi Monitor is a tool that provides access to information about the user's Wi-Fi environment and the current Wi-Fi connection. Xirrus Wi-Fi Monitor provides locations of Wi-Fi networks and their relative distance, wireless settings, Wi-Fi site survey, signal strength, IP and MAC addresses, SSID, channel, and security information.

Speedtest.net is an online performance measuring tool that tests the user's Internet connection bandwidth upload and download capabilities. We utilize this tool to measure our capabilities during different scenarios.

3. Influence of Obstacles

In less than ideal or realistic environments, obstacles are a significant issue. In this research we define obstacles as those things that degrade signal strength and interfere with Internet connectivity. In our research we address the following as obstacles; distance, non-supporting walls, and supporting walls. Each of these obstacles has a direct impact on signal strength and ultimately the total amount of data rate that is achievable. For our ideal baseline testing the signal strength for Wi-Fi was -58 dB(mW), and the strength for the Femtocell was -76 dB(mW).

We know that for both Wi-Fi and Femtocells signal strength is best when it travels through open spaces with little to no obstructions between wireless transmitters and wireless receivers. Even when there are few obstructions between the transmitter and receiver, the overall distance between them also affects the signal strength. Received signal power tends to fall rapidly with distance and obstructions; this is known as path loss. The capability to enable low signal to noise (SNR) operation is critical to address this. Different environments exhibit varying effects of path loss. Indoor path loss is typically worse than outdoor path loss due to greater attenuation of dense walls and objects (Chandrasekhar, 2008). To best represent these obstacles our research will take both obstacles and distance into consideration.

4. Testing Scenarios

We have chosen four different testing scenarios to best represent a realistic environment. These scenarios vary in distance from the router and take place both indoors and outdoors. These testing scenarios also include the addition of obstacles in the form of interior and exterior walls.

In Scenario1 we test an indoor area 25 feet away from the router with a non-supporting wall between the router and the testing device. Scenario 2 is the same distance of 25 feet but we have moved from indoors to outdoors with the router remaining indoors; therefore, there is both a non-supporting and a supporting wall between the router and the test device. In scenario 3 we remain outside with both a non-supporting and a supporting wall between the router and the testing device, but we move to 50 feet in distance. In scenario 4 we remain outdoors and continue to have both non-supporting and supporting walls between the router and the testing device but move further away, to a distance of 75 feet.

Utilizing WiEye, OpenSignal Maps, and Xirrus Wi-Fi monitor, we recorded the signal strengths for each scenario:

Baseline Test: -38 dB for Wi-Fi, and -56 dB for the Femtocell

Scenario 1: -71 dB for Wi-Fi (33 dB less than the baseline), and -86 dB for the Femtocell (30 dB less than the baseline)

Scenario 2: -74 dB for Wi-Fi (36 dB less than the baseline), and -88 dB for the Femtocell (32 dB less than the baseline)

Scenario 3: -76 dB for Wi-Fi (38 dB less than the baseline), and -88 dB for the Femtocell (32 dB less than the baseline)

Scenarion 4: -79 dB for Wi-Fi (41 dB less than the baseline), and -94 dB for the Femtocell (38 dB less than the baseline)

5. Baseline Test in Realistic Environments Evaluation

The results of testing in realistic environments are very interesting. They show a better resistance of the Femtocell to both the obstacles and distance. The signal strength of the Femtocell seems to also be slightly less attenuated than those of the Wi-Fi. Overall, throughout the scenarios Wi-Fi steadily declined in performance while the Femtocell actually increased in performance until the final scenario where they both dropped in downloading and uploading performance (Tables 16 and 17).

In order to understand these differences in performance we must start at the general carrier frequencies of the two platforms. Wi-Fi systems generally operate at 2.4 GHZ, and Femtocells operate at 1.8 GHZ. Since the Femtocell carrier frequency is lower than that of the Wi-Fi we know that this explains why the Femtocell experienced less power loss when compared to Wi-Fi (Chandrasekhar, 2008).

It can be seen from scenario 1 that a distance of 25 feet and the insertion of a non-supporting wall have significant effects on the Femtocell signal strength. The baseline test recorded -56 dB, and the result of scenario 1 was -86 dB, a difference of 30 dB. Wi-Fi, too, experienced a significant decrease in signal strength from a baseline of -38 dB to -71dB, a difference of 33 dB.

Comparisons of scenarios 2 and 3 suggest that the difference between inserting supporting and non-supporting walls has a greater effect on Wi-Fi than on Femtocells.

Wi-Fi experienced additional attenuations for both scenarios where Femtocell results stayed the same.

Zhen, et al. (2011) explains that propagation inside buildings is a serious problem for Wireless Local Area Network (WLAN) systems. Zhen goes on to state that Femtocells are a popular deployment options for coverage holes and capacity hotspot areas, and that “due to the poor outdoor-to-indoor propagation property of in-building environment, a dedicated wireless system installed inside the building is often preferred for providing indoor users high-data-rate services.“ Femtocells are cost-efficient techniques for this application and results have shown superior performance of the Femto system compared to other systems in providing high-data-rate services in most cases with a quality-guaranteed scheduler, while the centralized joint scheduling system gives the best performance. The centralized scheme can also help improve the system robustness in obtaining high performance even in the situation where access points are placed non-optimally (Zhen, 2011).

Scenario 3 suggests a further significant decrease in signal strength when transmitter and receiver reach a distance of 75 feet with intervening supporting and non-supporting walls. Noticeably, the decrease in signal strength is more remarkable for Femtocells (an additional 6 dB) than for WiFi (an additional 3 dB).

In summary, our realistic environment testing has shown that distance and obstacles weaken WiFi signals in a very significant way, much more than for Femtocells signals. In terms of performance in our realistic environment, we see that Wi-Fi download and uploading speeds tend to be more affected by a less than ideal environment. In contrast, the downloading and uploading performances of the Femtocell are only marginally affected by the obstacles of a realistic environment. The Femtocell, therefore, can be more capable in certain realistic environments. This suggests that Femtocells mounted on maneuver vehicles may provide better network access potential for dismounted personnel inside a neighboring structure than would be provided by a Wi-Fi access point mounted on the vehicle.

Test	Ping (ms)	Download Speed (Mbps)	Upload Speed (Mbps)	Signal Strength (dBm)
Baseline	25	18.87	4.08	-38
Scenario 1	26	14.81	4.05	-71
Scenario 2	33.1	15.04	3.96	-74
Scenario 3	27	12.05	3.96	-76
Scenario 4	27	9.51	3.86	-79

Table 16. Wi-Fi averages for realistic scenario testing

Test	Ping (ms)	Download Speed (Mbps)	Upload Speed (Mbps)	Signal Strength (dBm)
Baseline	51	8.06	0.72	-56
Scenario 1	155	9.70	0.60	-86
Scenario 2	467	11.83	0.97	-88
Scenario 3	609	10.66	1.06	-88
Scenario 4	311	4.82	0.53	-94

Table 17. Femtocell averages for realistic scenario testing

6. Scenario 1 Speedtest.net Results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	25	13.86	4.05
2	25	13.37	4.17
3	25	18.66	4.17
4	45	16.18	4.12
5	25	14.67	4.12
6	25	13.96	4.19
7	25	18.53	4.11
8	25	13.00	3.86
9	25	14.91	4.17
10	15	10.96	3.53
Average	26 ms	14.81 Mb/s	4.05 Mb/s

Table 18. Scenario 1 Wi-Fi connection

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	153	8.75	0.57
2	159	8.26	0.58
3	148	13.55	0.58
4	160	11.07	0.56
5	159	9.56	0.53
6	159	8.85	0.62
7	150	13.42	0.49
8	159	7.89	1.04
9	159	9.80	0.58
10	148	5.85	0.42
Average	**155 ms**	**9.70 Mb/s**	**0.60 Mb/s**

Table 19. Scenario 1 Femtocell connection

7. Scenario 2 Speedtest.net Results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	35	13.24	4.02
2	25	14.36	4.09
3	25	14.81	4.04
4	46	14.24	3.78
5	65	14.98	3.67
6	15	15.53	3.93
7	55	17.22	4.03
8	25	16.27	3.85
9	15	11.75	4.03
10	25	18.00	4.11
Average	**33.1 ms**	**15.04 Mb/s**	**3.96 Mb/s**

Table 20. Scenario 2 Wi-Fi connection

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	735	13.09	1.13
2	295	12.67	1.15
3	431	10.51	0.77
4	497	10.04	0.76
5	1040	7.88	1.17
6	315	15.38	1.10
7	575	15.53	0.77
8	344	11.97	0.77
9	162	7.55	1.29
10	273	13.70	0.78
Average	**467 ms**	**11.83 Mb/S**	**0.97 Mb/s**

Table 21. Scenario 2 Femtocell connection

8. Scenario 3 Speedtest.net Results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	15	12.13	3.83
2	45	13.26	4.18
3	25	15.67	3.91
4	35	8.27	3.40
5	25	15.45	4.08
6	25	8.54	4.15
7	25	13.07	4.04
8	25	11.67	3.86
9	25	10.16	4.06
10	25	12.30	4.11
Average	27 ms	12.05 Mb/s	3.96 Mb/s

Table 22. Scenario 3 Wi-Fi connection

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	431	14.20	1.32
2	508	13.77	1.24
3	579	9.65	0.64
4	174	16.01	0.58
5	920	7.41	1.58
6	923	6.37	1.32
7	581	10.68	0.78
8	522	11.57	1.01
9	658	9.14	1.34
10	268	7.82	0.82
Average	**609 ms**	**10.66 Mb/s**	**1.06 Mb/s**

Table 23. Scenario 3 Femtocell connection

9. Scenario 4 Speedtest.net Results

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	25	9.54	3.97
2	25	5.63	4.07
3	15	7.53	4.06
4	25	9.56	3.93
5	25	8.48	3.85
6	25	8.80	3.91
7	45	11.97	4.06
8	25	10.72	3.53
9	25	10.15	3.33
10	35	12.68	3.90
Average	27 ms	9.51 Mb/s	3.86 Mb/s

Table 24. Scenario 4 Wi-Fi connection

Test Number	Ping (ms)	Download Speed (Mb/s)	Upload Speed (Mb/s)
1	298	4.39	0.52
2	323	2.98	0.61
3	162	3.92	0.57
4	271	5.35	0.51
5	340	3.99	0.50
6	298	4.05	0.51
7	502	6.34	0.61
8	271	5.57	0.49
9	270	5.68	0.43
10	378	5.96	0.51
Average	**311 ms**	**4.82 Mb/s**	**0.53 Mb/s**

Table 25. Scenario 4 Femtocell connection

C. ACCESSING THE INTERNET THROUGH HTTP TESTS

1. Introduction

Hypertext Transfer Protocol (HTTP) is a stateless application level protocol that is used to transfer data on the Internet. Web browsers and servers exchange information in accordance with the rules of HTTP. HTTP is a request/response protocol, which means that a web browser will initiate a request to a server and the server in turn sends a response. HTTP deals with every web page and is used in every action involved in Internet "web surfing."

As HTTP is the foundation of data communication for the World Wide Web (http://www.w3.org) it is very important to our research. Our testing will therefore address HTTP downloading and point out the differences between the capabilities of Wi-Fi and Femtocell in terms of downloading data from the Internet. We will also deal with the differences between the way Femtocells and Wi-Fi access the Internet.

2. Software Used

To address these areas we will use a freeware tool called Downtester. Downtester is a tool that tests Internet download speeds in multiple locations throughout the world. It allows the user to choose URLs and will systematically test the download speed of each. (http://www.nirsoft.net) For this research we have chosen the following six URLs: http://www.google.com, http://www.facebook.com, http://www.yahoo.com, http://www.baidu.com, http://www.youtube.com, and http://www.cnn.com.

We will also use the Downtester program to measure the time to download files of varying sizes. In our research we will test files that are 20 MB, 50MB, 100MB, and 200MB in size (see Tables 27 – 34). These sizes were chosen to represent the average users downloading needs, as stipulated in Chapter 3. Finally, we will also be using HTTP Analyzer, a tool that allows the user to monitor, trace, and analyze HTTP traffic in real-time (http://www.ieinspector.com/httpanalyzer.com).

3. HTTP Upload/Download Test Results

File Size	Wi-Fi Speed (Kbytes/s)	Femtocell Speed (Kbytes/s)	Wi-Fi Speed (Mbits/s)	Femtocell (Mbits/s)
20MB	888.30	488.06	7.28	3.99
50MB	954.54	524.41	7.82	4.29
100MB	873.66	479.98	7.16	3.93
200MB	413.25	227.03	3.39	1.95

Table 26. Average results comparing Wi-Fi and Femtocell

Table 26 shows our HTTP testing downloading rates that are on average with the results from our previous Wi-Fi and Femtocell downloading speed comparison testing. Wi-Fi's downloading speed increases initially and then with the larger size files it falls a little at first then it drops significantly. The Femtocells is comparable in its results. It too averages approximately 4 Mbits/s until it hits the largest file where it falls to approximately 2 Mbits/s. These results show that both Femtocells and Wi-Fi are comparable when accessing files of various sizes over the Internet. Only the biggest files appear to slow the downloading performances of both Femtocells and Wi-Fi.

4. Speed Results for 20MB Files

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	872.3	7.15
2	839.6	6.88
3	884.6	7.25
4	566.1	4.64
5	880.4	7.21
6	974.8	7.99
7	849.6	6.96
8	951.5	7.79
9	1102.3	9.03
10	961.8	7.88
Average	**888.30 KB/Sec**	**7.28 Mbps**

Table 27. 20 MB file Wi-Fi connection results

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	479.3	3.92
2	461.3	3.78
3	486.0	3.98
4	311.1	2.54
5	483.7	3.96
6	535.6	4.39
7	466.8	3.82
8	522.8	4.28
9	605.6	4.96
10	528.4	4.32
Average	**488.06 KB/Sec**	**3.99 Mbps**

Table 28. 20 MB file Femtocell connection results

5. Speed Results for 50MB Files

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	963.3	7.89
2	974.2	7.98
3	929.6	7.62
4	870.1	7.13
5	745.9	6.11
6	1052.2	8.62
7	959.6	7.86
8	1003.9	8.22
9	1091.6	8.94
10	955.0	7.82
Average	**954.54 KB/Sec**	**7.82 Mbps**

Table 29. 50 MB file Wi-Fi connection results

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	529.2	4.33
2	535.2	4.38
3	510.7	4.18
4	478.0	3.91
5	409.8	3.35
6	578.1	4.73
7	527.2	4.31
8	551.5	4.51
9	599.7	4.91
10	524.7	4.29
Average	**524.41 KB/Sec**	**4.29 Mbps**

Table 30. 50 MB file Femtocell connection results

6. Speed Results for 100MB Files

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	930.1	7.62
2	947.8	7.76
3	1125.3	9.22
4	944.5	7.74
5	1035.8	8.49
6	873.6	7.16
7	936.4	7.67
8	941.8	7.72
9	627.5	5.14
10	373.8	3.06
Average	**873.66 KB/Sec**	**7.16 Mbps**

Table 31. 100 MB file Wi-Fi connection results

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	511.0	4.18
2	520.7	4.26
3	618.2	5.06
4	518.9	4.25
5	569.1	4.66
6	480.0	3.93
7	514.5	4.21
8	517.4	4.24
9	344.7	2.82
10	205.3	1.68
Average	**479.98 KB/Sec**	**3.93 Mbps**

Table 32. 100 MB file Femtocell connection results

7. Speed Results for 200MB Files

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	674.4	5.52
2	412.4	3.38
3	343.6	2.81
4	393.1	3.22
5	358.2	2.93
6	318.5	2.61
7	336.4	2.76
8	379.6	3.11
9	403.9	3.31
10	512.7	4.20
Average	**413.25 KB/Sec**	**3.39 Mbps**

Table 33. 200 MB file Wi-Fi connection results

Test Number	Speed (Kbytes/s)	Speed (Mbits/s)
1	370.5	3.03
2	226.5	1.85
3	188.7	1.54
4	215.9	1.76
5	196.8	1.60
6	175.0	1.43
7	184.8	1.51
8	208.5	1.70
9	221.9	1.81
10	281.7	2.30
Average	**227.03 KB/Sec**	**1.85 Mbps**

Table 34. 200 MB file Femtocell connection results

8. Real Time HTTP Monitoring

After establishing our basic speeds for downloading various size files via HTTP, we now move on to the real time monitoring of HTTP traffic. In this section of our research we analyze the process of HTTP traffic. We will start with the components for the websites of the six chosen websites. These include Google.com, Facebook.com, Youtube.com, Yahoo.com, CNN.com, and Baidu.com.

All websites are made up of similar content. “We define content broadly as the stuff in your web site.” (Rosenfeld et al, 1998) In general we view data, applications, images, and video when we access a website, which are all essentially files; however, the way the files are handled and the sensitivity to loss or delay is particular to specific file types, based on the requirements of the using applications. As shown in Figures 10 and 11, our research will break this basic content into percentages of the total amount of components in each respective website. We will use this as a reference when we then break down the six websites into four phases of the HTTP request. The four phases we will cover are the connect phase, content request phase, waiting phase, and receive first to last phase. We will then compare the performance of both Wi-Fi and Femtocell in download these websites.

In our tests the connect phase represents the Transmission Control Protocol (TCP) level connection time. This is the time that a new TCP level connection is established with the web server. The send first to last phase represents the time required to send the HTTP request message to the server. This value depends on the amount of data that is sent to the server. The wait phase is the idle time taken to receive a response message from the server. This value includes network delay time and web server processing time. Finally, the receive first to last phase is the time that you receive the response message from the web server. This value depends on the size of the return data and the network bandwidth.

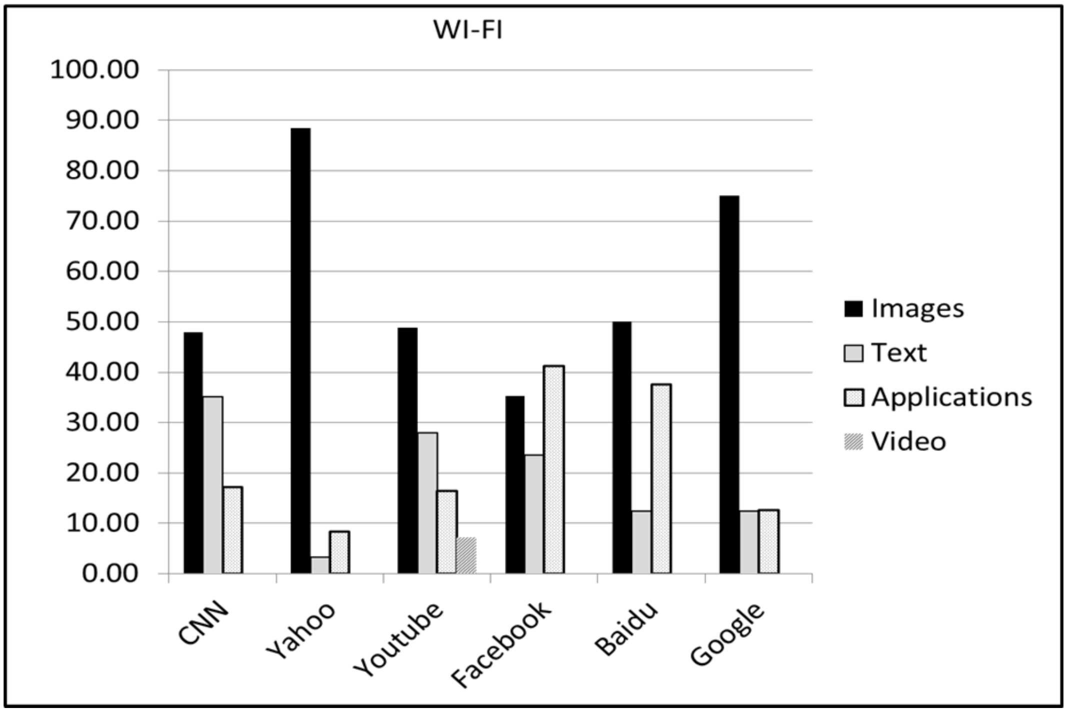

Figure 10. Percentage of Wi-Fi accessed website images, text, applications, and video

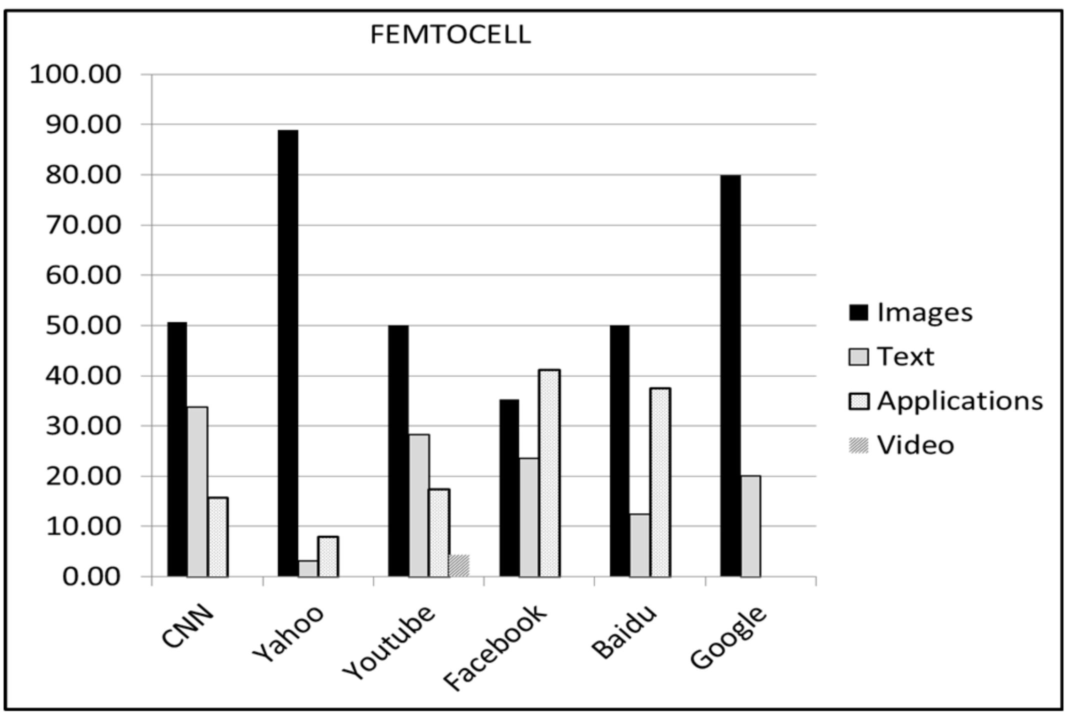

Figure 11. Percentage of Femtocell accessed website images, text, applications, and video

Figures 10 and 11 show the website profile characteristics based on the percentage of total objects present in each of the listed websites. From the information provided by Tables 35 and 36, we can see where the biggest areas are and which affect performance the most. Images are typically the largest items on most websites, these are followed by applications and text. Only one website visited contained video files.

Wi-Fi	**Images**	**Text**	**Applications**	**Video**
CNN	48	35	17	0
Yahoo	89	3	8	0
YouTube	49	28	16	7
Facebook	35	24	41	0
Baidu	50	13	37	0
Google	75	12	13	0
Average %	**58%**	**19%**	**22%**	**1%**

Table 35. Wi-Fi profile characteristic averages

Femtocell	**Images**	**Text**	**Applications**	**Video**
CNN	50	34	16	0
Yahoo	89	3	8	0
YouTube	50	28	18	4
Facebook	35	24	41	0
Baidu	50	13	37	0
Google	80	20	0	0
Average %	**59%**	**20%**	**20%**	**1%**

Table 36. Femtocell profile characteristic averages

Wi-Fi	**Connect**	**Send**	**Wait**	**Receive**
CNN	19	1	48	32
Yahoo	3	1	62	34
YouTube	16	1	67	16
Facebook	24	1	74	1
Baidu	1	1	97	1
Google	5	3	62	30
Average %	**11%**	**1%**	**69%**	**19%**

Table 37. Wi-Fi HTTP breakdown

Femtocell	Connect	Send	Wait	Receive
CNN	11	1	40	48
Yahoo	13	1	43	43
YouTube	41	1	49	9
Facebook	15	1	83	1
Baidu	45	1	53	1
Google	1	1	69	29
Average %	**21%**	**1%**	**56%**	**22%**

Table 38. Femtocell HTTP breakdown

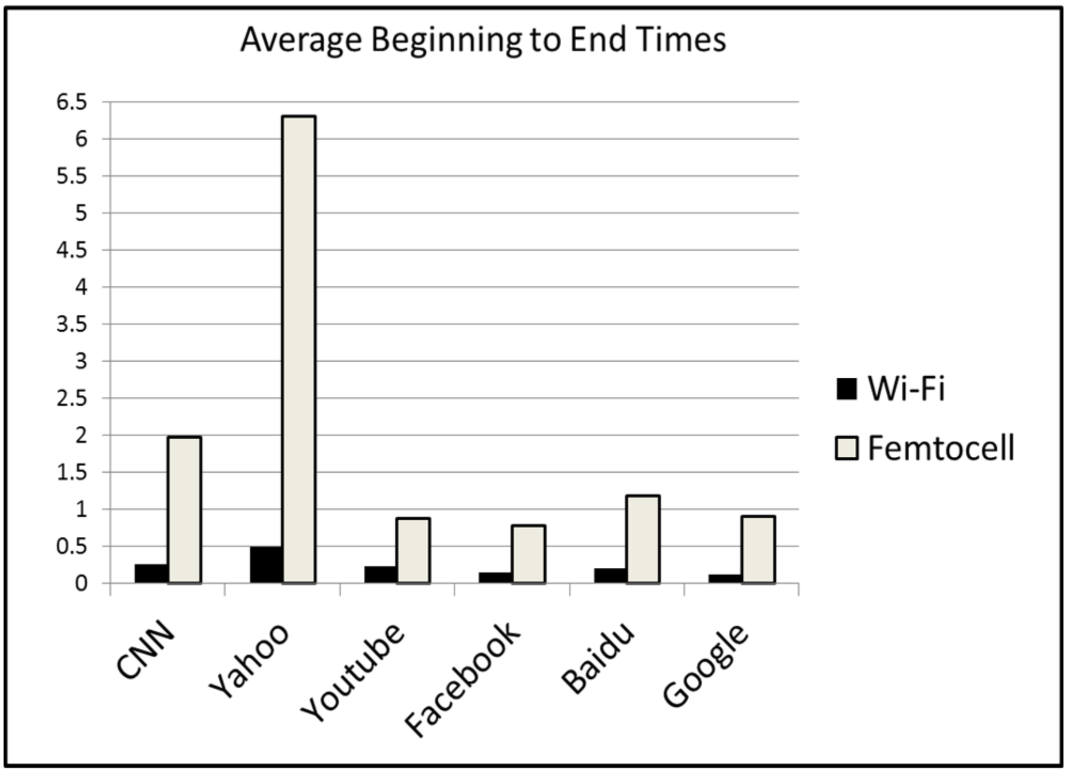

Figure 12. Average downloading time from beginning to end (in seconds)

9. Analysis of HTTP Traffic Monitoring Testing

Dissecting the HTTP process in our testing provides even better insight into the issues related to HTTP handling by both Femtocells and WiFi across a number of different sites and applications. Our research shows that the average loading time for a page is typically 2 seconds for the Femtocell and slightly less than that for Wi-Fi. These speeds are dependent on the page that is accessed.

As shown in our research the largest component of our selected websites is images, at approximately 58% for both Wi-Fi and Femtocell. Applications were the second most used component at 20% for both, next is text at 20%, and finally video was rarely used and was measured at 1%.

We next look at the process of accessing a website. The four stages of accessing a website are connection, sending, waiting, and receiving. Our research has shown that the largest percentage of these four stages was wait time (Tables 37 and 38, and Figure 12). It was 69% of the total process for Wi-Fi and 56% for Femtocell. The next largest percentage was receiving time at 19% Wi-Fi, and 22% for Femtocell. Connect time for Wi-Fi was 11% and for Femtocells it was 21%. Finally, the smallest percentage, sending, measured at approximately 1%.

Our research shows us that the difference in loading time is not necessarily dependent on the content. The slight difference can be explained by the Femtocells slower down-load speed and the additional delay can also be attributable to the long mobile operator chain between the Home Node (HNB) and global IP access to the server in the case of Femtocells, while WiFi can access directly to the global IP network and hence to the server.

D. STREAMING OF FILES THROUGH RTP TESTS

1. Introduction

To test streaming capabilities we utilize Real-time Transport Protocol (RTP) and Real-time Transport Control Protocol (RTCP). These protocols provide end-to-end network transport functions for applications transmitting real-time data, such as interactive audio and video. Using RTP/RTCP we can analyze videos of different sizes by using a packet sniffer program. Utilizing a packet sniffer program we can analyze the stream for information such as sequence errors, jitter, packet losses, etc. This will provide a comparison between the performances of Femtocells and Wi-Fi while streaming a video.

2. Software Used

We started with a streaming video test from myspeed.visualware.com that measures Real Time Streaming Protocol (RTSP) video and interlaced audio to identify high packet jitter and packet loss that causes poor quality video. We then performed tests using the packet analyzer, Wireshark. Utilizing Wireshark and a VideoLAN Client (VLC) player we selected various size video files (20MB, 40MB, 60MB, and 100MB) to stream (http://www.videolan.org). While streaming, we used Wireshark to capture packets for analysis. The VLC player provides the option to stream video that has been downloaded. We utilized this option to stream these video files of differing sizes via RTP to 224.1.1.1 using port 5004. Wireshark was opened and started the capture of packets when the video began playing.

3. Video and Audio Testing

To start, we ran tests on the quality of the video and audio over IP. This test specifically looked at jitter and packet loss. In these results we saw the variance of User Datagram Protocol (UDP) RTT over time, providing insight into the jitter experienced. The RTT variance must be kept to a minimum otherwise video quality may be degraded. In this test, the measure of jitter is the difference in time that each packet takes to reach its destination. In an ideal case, each packet sent would take the same time to travel between the server and the client. In our tests, we saw that Wi-Fi and Femtocell measurements in regards to jitter are very close (Tables 39 and 40). For video, Wi-Fi averages 1.54 ms and Femtocell 2.06 ms. Audio jitter is very close, with Wi-Fi averaging left audio channel jitter at 1.42 ms and right audio channel jitter at 1.44 ms. Femtocells audio jitter measures left channel 1.18 ms and right channel 1.26 ms. In this case the Femtocell has less jitter in its audio channels. Our test also compared the amount of packet loss between Wi-Fi and Femtocells. This was also very close, with Wi-Fi having no packet losses in either left and right audio channels or video. Femtocells had 0.16 percent loss in all three respective categories (Table 40).

The final area addressed in this test was packet order. Packet order is a measurement of how many packets arrive in order. Packets do not necessarily take the same route or the same time to reach their destinations and when they arrive out of order it may lead to delayed or even discarded packets. In our video test Wi-Fi achieved 100% packet order and Femtocell 99.82%. Wi-Fi also scored 100% in both left and right audio packet order, whereas Femtocell scored 99.82%.

Test Number	Video Jitter (ms)	Video Loss (%)	Video Packet Order (%)	Left Audio Jitter (ms)	Left Audio Loss (%)	Left Audio Packet Order (%)	Right Audio Jitter (ms)	Right Audio Loss (%)	Right Audio Packet Order (%)
1	1.5	0	100	1.3	0	100	1.4	0	100
2	3.2	0	100	3.2	0	100	3.3	0	100
3	1.6	0	100	1.2	0	100	1.2	0	100
4	0.7	0	100	0.7	0	100	0.7	0	100
5	0.7	0	100	0.7	0	100	0.6	0	100
Average	**1.54 ms**	**0%**	**100%**	**1.42 ms**	**0%**	**100%**	**1.44 ms**	**0%**	**100%**

Table 39. Wi-Fi audio video test

Test Number	Video Jitter (ms)	Video Loss (%)	Video Packet Order (%)	Left Audio Jitter (ms)	Left Audio Loss (%)	Left Audio Packet Order (%)	Right Audio Jitter (ms)	Right Audio Loss (%)	Right Audio Packet Order (%)
1	1.3	0	100	1.0	0	100	0.9	0	100
2	3.9	0.8	99.1	2.0	0.8	99.1	2.3	0.8	99.1
3	2.3	0	100	1.0	0	100	1.1	0	100
4	1.4	0	100	0.9	0	100	1.0	0	100
5	1.4	0	100	1.0	0	100	1.0	0	100
Average	**2.06 ms**	**0.16 %**	**99.82%**	**1.18 ms**	**0.16 %**	**99.82%**	**1.26 ms**	**0.16 %**	**99.82 %**

Table 40. Femtocell audio video test

4. Analysis of Video Streaming Through RTP Test Results

As videos vary in size depending on the quality and content, we streamed very basic videos of average quality and with few special effects and audio variances (teaching and lecture videos). Our 20MB video streamed for ten minutes and, as shown for Wi-Fi, there are no packet losses or sequence errors. Utilizing the Femtocell for the same 20MB streaming video also reflected zero percent packet loss and no sequence errors. Both Wi-Fi and Femtocell show the same results for this size file (Table 41). This is most likely due to the low amount of data rate of the video streamed. At this lower level there are no packet losses and the downlink channel is not overloaded. This is very close to an ideal case scenario for both Wi-Fi and Femtocell.

When we proceeded to the next set of files, the 40MB streaming video size. At this file size the results for Wi-Fi began to show packet losses and sequence errors. Wi-Fi experienced a 41.95% packet loss and an average of 8.8 sequence errors per file (Table 42). While watching the streaming video of this file size you begin to see a slight degradation in the quality of the video. The packet losses and sequence errors are having an effect on the video but the viewer is still able to watch the video without too much frustration. Our results from the Femtocell were still outstanding. The packet losses were zero and there were no sequence errors. Streaming the video over Femtocell is noticeably smoother than the Wi-Fi at this point.

Streaming video files of 60MB are approximately thirty minutes in length. Our Wi-Fi streaming tests showed a continuing decline. The packet losses increased to 46.09% and the sequence errors are just under 8 per file. With these levels observed more distortion and a few moments of shuttering (or quick stopping and jumping). The Femtocell began to experience packet loss and sequence errors streaming this file size. The results from the Femtocell were 28.92% packet loss and 3.6 sequence errors (Table 43). Here we also observed slight distortion and image shuddering and jumping.

Videos of 100MB are generally a higher quality 30–40 minute video or a medium quality 50 minute video. Our results showed a significant amount of packet loss and sequence errors for the Wi-Fi and Femtocell at this size video file. Wi-Fi results reflected an average of 81.95% packet loss and 18 sequence errors. With the Wi-Fi video saw complete stoppage at several points and distortion. There are some instances with missing frames that may be attributed to the high levels of packet loss. For this file size the Femtocell experienced packet losses of 70.79% and 3.8 sequence errors (Table 44). The viewing quality is better than the Wi-Fi, but still almost unusable.

As can be seen by our research Femtocells outperform Wi-Fi in terms of RTP video streaming applications. An understanding of the access protocols used by Femtocells and WiFi networks provide insight into the possible reason for the difference in the performance of these networks for streaming content. The 3GPP release 6 describes the High Speed Uplink Packet Access (HSUPA) scheme used by Femtocell devices; this is likely the key to the Femtocells RTP streaming success. This scheme tends to be more efficient in streaming because it utilizes the available spread spectrum Dedicated Physical Data Channel (DPDCH), which transports RTP frames very efficiently (Hu, et al., 2012). As streaming operates in a continuous fashion channels are assigned at the beginning of the stream and these same channels remain used throughout. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme used by WiFi networks is a contention=based access scheme that relies on collision recovery mechanism to limit the effect of congestion on the link, but it does not eliminate collisions. This scheme is less effective for streaming RTP scenarios as it does not dedicate resources to the specific stream. This is due to the fact that Wi-Fi cannot make full use of its capacity due to its reliance on contention-based access. This is in part caused by Wi-Fi having to move through several protocols this leads to a degradation of efficiency throughout the streaming process. In conclusion streaming through RTP emphasizes the strengths of Femtocells versus Wi-Fi. Femtocells operate efficiently with much less packet loss and sequence errors for streaming video files of various sizes (Figure 13).

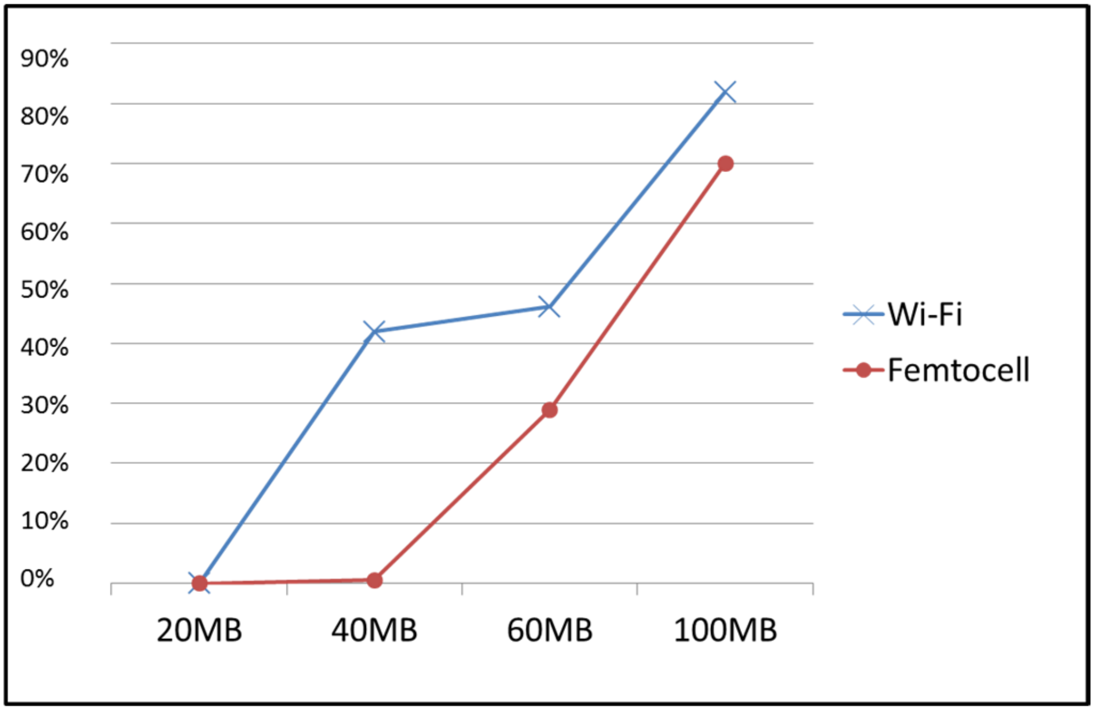

Figure 13. Wi-Fi Femtocell packet loss

5. Test Results for 20MB Streaming Video

Test Number	Wi-Fi Packet Loss (%)	Wi-Fi Sequence Errors	Femtocell Packet Loss (%)	Femtocell Sequence Errors
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
Average	0%	0	0%	0

Table 41. 20 MB streaming video results

6. Test Results for 40MB Streaming Video

Test Number	Wi-Fi Packet Loss (%)	Wi-Fi Sequence Errors	Femtocell Packet Loss (%)	Femtocell Sequence Errors
1	41.69	9	0	0
2	40.02	8	0	0
3	46.19	9	0	0
4	41.07	9	0	0
5	40.80	9	0	0
Average	41.95%	8.8	0%	0

Table 42. 40 MB streaming video results

7. Test Results for 60MB Streaming Video

Test Number	Wi-Fi Packet Loss (%)	Wi-Fi Sequence Errors	Femtocell Packet Loss (%)	Femtocell Sequence Errors
1	45.40	8	28.88	4
2	40.02	8	27.41	4
3	44.90	7	30.30	3
4	49.30	6	28.55	3
5	50.80	9	29.46	4
Average	46.09%	7.6	28.92%	3.6

Table 43. 60 MB streaming video results

8. Test Results for 100MB Streaming Video

Test Number	Wi-Fi Packet Loss (%)	Wi-Fi Sequence Errors	Femtocell Packet Loss (%)	Femtocell Sequence Errors
1	80.20	19	70.79	4
2	78.50	16	68.28	3
3	82.11	20	71.53	4
4	83.00	18	70.02	4
5	86.10	17	69.40	4
Average	81.95%	18	70.00%	3.8

Table 44. 100 MB streaming video results

E. VOIP TESTING

1. Introduction

Voice over IP (VoIP) is voice delivered using Internet protocol. This means sending voice information in digital form in discrete packets rather than in the traditional circuit switched protocols used in Public Switched Telephone Networks (PSTN). It is generally accepted that the better the upload/download speed the better the connection during a VoIP call (Chandrasekhar, 2008). In the case of VoIP, jitter and packet loss are significant factors that can lead to poor quality or limited usability.

2. Software Used

To perform these tests we used the online testing programs, VoIPreview.org/voipspeedtester and myspeed.visualware.com. VoIPreview is a program that evaluates the parameters of a VoIP phone call (http://voipreview.org). Myspeed provides the calculations of all parameters necessary for a successful VoIP call and establishes the evaluation of an all-encompassing Mean Opinion Score (MOS) (Table 45) as described in Chapter 3 (http://www.myspeed.visualware.com). The score depiction is provided again for ease of reference. The range of 4.0 to 4.5 is generally accepted as the level that provides a quality VoIP call. In contrast, any value below 3.5 is considered unacceptable.

Score	Quality of Communication
1	Impossible to communicate.
2	Very annoying. Nearly impossible to communicate.
3	Annoying
4	Fair. Imperfections can be perceived, but sound still clear. This is the range for cellular phones.
5	Perfect. Like face-to-face conversation or radio reception.

Table 45. Mean Opinion Score (MOS)

3. Analysis of VoIP Test Results

When assessing the differences between Wi-Fi connections and Femtocell connections in regards to VoIP we return to the same criteria as our previous tests; jitter, packet loss, and upload/download speed and consistency. Figure 14 shows the VoIP requirements for jitter and packet loss.

When considering jitter with respect to VoIP it needs to be less than 5ms to reach standard quality. Our testing shows both Wi-Fi and Femtocells jitter scores are in the standard quality range. Wi-fi jitter averaged 6.8 ms and Femtocell jitter averaged 16.45 ms. While the Wi-Fi scores were better, both are within acceptable VoIP communications criteria (http:www.voip-info.org).

For VoIP applications, packet loss needs to be less than 1% to be considered standard quality. Our testing show packet loss for Wi-Fi is 0%, which is perfect. The packet loss for Femtocell was very close, measuring 0.06%. Both Wi-Fi and Femtocells score in the radio quality category, which is perfect for VoIP communications.

Packets are very time dependent when it comes to media based applications like VoIP. If the packet arrives too late it is discarded and there is a degradation of quality. The packet discards experienced during our testing was the first area where Wi-Fi pulls noticeably ahead of the Femtocell. In this area where even a slight loss of information can noticeably degrade performance Wi-Fi had 0.04% packet discards and Femtocell had 1.24%.

With respect to an overall quality rating, as indicated by the assessed MOS score (see Table 45) Wi-Fi score was 3.92 and the Femtocell MOS score was 3.54. Both of these scores fall in the fair category, where imperfections can be perceived but sound is still clear for the most part.

Lastly our test considered average round trip time, which is related to jitter; the quicker the average RTT the better the connection. The average RTT for the Femtocell-based connection was longer than for the Wi-Fi. On average, the trip time for Wi-Fi was 28ms and Femtocells average time was 44ms. This is double the trip time and again is due to the longer connection process. However, 44 ms is still well within standard for VoIP service (http:www.voip-infor.org).

JITTER		PACKET LOSS
0 ms		0%
1 ms	←Radio Quality→	
2 ms		0.2%
3ms		0.5%
5 ms	←Standard Quality→	1%
10 ms		2%
20 ms	←Broken Sound→	5%
40 ms	←VoIP Unsupportable→	50%
100 ms		100%

Figure 14. MyConnection server from 1999–2010 Visualware VoIP chart

In summary, both Wi-Fi and Femtocell meet the requirements for standard quality or better in these VoIP tests. Wi-Fi has a slight, but only negligible edge, over Femtocells in terms of performance issues for packet discards and total averaged round trip time.

4. VoIP Test results

Test Number	Achieved Download Speed (Mbps)	Achieved Upload Speed (Mbps)	Download Service Consistency (%)	Upload Service Consistency (%)	Average Trip Time (ms)
1	8.97	4.28	63	97	29
2	9.72	4.25	96	97	29
3	8.41	3.97	93	92	28
4	5.96	4.12	56	97	25
5	7.84	3.85	72	96	29
Average	8.18 Mbps	4.09 Mbps	76%	96%	28 ms

Table 46. Wi-Fi connection Voipreview.org/voipspeedtester results

Test Number	Achieved Download Speed (Mbps)	Achieved Upload Speed (Kbps)	Download Service Consistency (%)	Upload Service Consistency (%)	Average Trip Time (ms)
1	8.14	304	90	45	49
2	6.78	259	56	21	38
3	7.93	398	69	54	45
4	9.05	536	86	81	43
5	8.24	193	90	56	45
Average	8.03 Mbps	338 Kbps	78.2 %	51%	44 ms

Table 47. Femtocell connection Voipreview.org/voipspeedtester results

Test Number	Jitter User to Server (ms)	Jitter Server to User (ms)	Packet Loss User to Server (%)	Packet Loss Server to User (%)	Packet Discards (%)	MOS Score
1	3.0	4.0	0	0	0	4.1
2	3.4	13.9	0	0	0	3.9
3	3.8	24.1	0	0	0.2	3.5
4	2.9	3.8	0	0	0	4.1
5	3.9	4.3	0	0	0	4.0
Average	**3.4 ms**	**10.2 ms**	**0%**	**0%**	**0.04%**	**3.92**

Table 48. Wi-Fi connection myspeed.visualware.com results

Test Number	Jitter User to Server (ms)	Jitter Server to User (ms)	Packet Loss User to Server (%)	Packet Loss Server to User (%)	Packet Discards (%)	MOS Score
1	4.0	12.2	0	0	0	3.9
2	19.6	16.6	0	0	4.4	3.7
3	5.5	52.7	0	0	0.4	2.8
4	7.2	24.2	0.2	0	0.8	3.6
5	5.8	16.8	0	0.4	0.6	3.7
Average	**8.4 ms**	**24.5 ms**	**0.04%**	**0.08%**	**1.24%**	**3.54**

Table 49. Femtocell connection myspeed.visualware.com results

In this chapter we have performed an in-depth analysis on the capabilities and performance of both Wi-Fi and Femtocells. We began by establishing a baseline that pointed out the benefits of Wi-Fi's better data rate over that of Femtocells. However, when we performed our testing in less than ideal conditions we learned that Wi-Fi tends to suffer more from the effects of obstacles and distance. Our testing on HTTP web accessing we learned that Wi-Fi performs better due to the fact that it was built and designed for this purpose. Femtocells on the other hand, have a more complicated Internet accessing processes that costs it in terms of both time and performance when "web surfing." The testing performed in RTP file streaming showed that Femtocells tend to operate more efficiently for larger files than Wi-Fi. Finally our VoIP testing has shown that Wi-Fi performs slightly better than Femtocells. We will now move on to summarize our testing and provide conclusions as well as recommendations for areas for future research.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A. CONCLUSIONS

The purpose of this research was to evaluate the utility of Femtocells as a means of providing remote access to smart-phone user where commercial cellular coverage was unavailable. This involved comparing the performance and capabilities provided by Femtocell enabled networks to that of a traditional wireless Wi-Fi network. To do this our research evaluated the performance and capabilities of these two technologies through several use-cases, applications, and scenarios.

Our research began with a series of baseline tests and assessments of the performances of these two technologies in near ideal conditions. These tests were performed again in less than ideal conditions, containing both obstructions and over distances more typical of conditions experienced by deployed, dismounted force elements or first responders. In ideal conditions, the baseline tests confirmed that Femtocells do extend access to standard cellular systems, but they offer much reduced data rates to a user than does Wi-Fi enabled access. This is due to the smaller channel capacity of the commercial-off-the-shelf 3G Femtocells. Our field tests provided an interesting insight, however, in that the difference in raw data rates was significantly reduced when the environment (obstacles and distance) were entered into the equation. When the context is in a realistic field environment, the Femtocells deficiencies are significantly reduced as compared to those of the WiFi enabled access network under the same environmental conditions.

A potential weakness of the Femtocell is the complicated process of accessing the Internet. To access the global IP, Femtocells must go through multiple steps in the mobile operator’s domain and consequently each single interaction is more time consuming and complex. This complicated process adds time and affects performance. This is not the case for Wi-Fi which connects directly to the Internet. The test results have shown that this is not a significant time difference it is just a different way of accessing the Internet, as demonstrated by performance tests in the area of Internet browsing, or “surfing,” using the HTTP protocol.

However, our testing of web browsing through HTTP and file streaming through RTP indicated very different results between Femtocells and Wi-Fi hosted access networks. With HTTP web browsing, Wi-Fi does better than the Femtocell-hosted access as it has the larger shared channel capacity. It must be noted, though, that the contention-based access mechanism of WiFi hosted networks makes it more susceptible to congestion (i.e., several traffic loads associated with increased numbers of users) than does a Femtocell-based access network. In RTP testing, the Femtocell performed better than Wi-Fi. The complexity and time-consuming Internet accessing process for the Femtocell, that is, routing all data traffic through the cellular provider’s core network in order to access the Internet, does not appear to be as significant of an issue with streaming traffic performance as it is with general web access. RTP streaming is essentially a one-way process, with very long sequences that are sensitive to variances in packet delays. This process does not penalize the Femtocell-hosted access networks as much as it does Wi-Fi due to the shared channel nature of the Wi-Fi-hosted network, which is susceptible to interference from neighboring Wi-Fi sources, which degrades the respective application performance. Our tests demonstrated this by showing that Femtocells operate correctly, with little or no packet loss, for much larger files than WiFi; and even under more extreme loads, Femtocells packet losses are half that of WiFi, until the point where the communications collapse.

Finally, we evaluated the VoIP supporting protocols offered by both Femtocell and Wi-Fi. Here we found that both Wi-Fi and Femtocell meet the requirements for standard or better quality for VoIP operations. Wi-Fi has a slight, but only negligible edge, over Femtocells in terms of performance issues for packet discards and total averaged round trip time (latency).

In summary, in baseline testing Wi-Fi provides a better data rate to the user than does Femtocells. Wi-Fi, however, suffers more from the effects of obstacles and distance. In HTTP web accessing, Wi-Fi excels because it was built and designed for this purpose. Femtocells have complicated Internet accessing processes, requiring an existing relationship with a cellular provider. Further, accessing the Internet through the femtocell requires redirection through that cellular provider exacerbating latency issues. In RTP file streaming Femtocells operate more efficiently for larger files showing less packet losses than Wi-Fi. Finally in VoIP testing Wi-Fi performs slightly better than Femtocells.

The use of smartphones, tablets, and other wireless devices is becoming increasingly prevalent and is driving the need for innovations in wireless data technologies to provide more capacity, higher speed connections, and higher quality of service. Femtocells can provide a useful way for mobile operators to offer a better user experience and deliver broadband services indoors consistently and reliably for a comparable context of application, distances, and obstacles.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

One of the most common issues with Internet connectivity is the effect of multiple users on performance. Future research should explore how multiple users connected simultaneously could affect the behavior and performance of femtocells and Wi-Fi provided connectivity. Researchers could create a scenario where multiple users access the network simultaneously and perform tests that monitors traffic through all network connections. They could then measure Internet connection bandwidth upload and download rates to compare performance and capabilities.

Future research regarding utilizing the Femtocell in military applications would be beneficial. Research would need to be conducted that would create an architecture to incorporate the Femtocell in field environments and tests is abilities to perform in deployed situations. Issues requiring investigation include policy constraints as well, particularly in international contexts.

Research into the capabilities of utilizing Femtocells as mobile phone range extenders in remote areas on bases, in office or barracks, and even on ships would be beneficial.

Finally, in this research we tested Femtocell and Wi-Fi capabilities in both ideal and field-like conditions to gain an understanding of their respective capabilities and performance. Future research could utilize the same scenarios to tests impacts to HTTP accessing, and streaming via RTP, as well as VoIP, as this research addressed these impacts for the ideal environment only.

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